Safety Assessment of
Radioactive Waste Repositories

Systematic Approaches to Scenario Development

A report of the NEA Working Group
on the Identification and Selection
of Scenarios for Performance Assessment
of Radioactive Waste Disposal

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

PARIS 1992

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- 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 has a special status at OECD (agreement of 28th October 1961).

The ECD 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 harmonization 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 the long-term safety of these repositories, 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.

The NEA Performance Assessment Advisory Group (PAAG) was established early in 1986 with the mandate to advise the Radioactive Waste Management Committee on technical aspects of the performance assessment of radioactive waste disposal systems and to help co-ordinate NEA activities in this area. PAAG provides an international forum for discussion and information exchange between OECD countries on performance assessment matters. PAAG's initiatives include the establishment of working groups, sponsorship of workshops and symposia, and the preparation of studies on important issues. The overall aim of the PAAG programme is to assist in the development of methods and tools of high quality for the assessment of the safety of radioactive waste repositories, and to promote a balanced and coherent use of these methodologies within radioactive waste disposal programmes.

One early initiative by PAAG was to set up a Working Group on the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal. This Working Group, whose members are listed in Annex 1, has extensively reviewed approaches to, and experiences with, scenario development in OECD countries. This final report by the Working Group is based on the extensive literature available, and provides a state-of-the-art summary of approaches to scenario development. Material prepared by working group members and their colleagues for presentation and discussion at the meetings of the Scenarios Working Group has provided an invaluable input to the preparation of this report.

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.

ABSTRACT

This report describes and discusses the current approaches to the identification and selection of scenarios for the safety assessment of radioactive waste disposal systems. The scenario development process blends information on site and waste characteristics, and the understanding of the various processes at work within the disposal system, with the judgement of appropriately experienced scientists and others. In this process, it is important to follow systematic procedures and to carefully document each step so that it is amenable to scrutiny. There is wide agreement on the general approach that should be taken for the identification, classification, and screening of phenomena that need to be considered. Several approaches have been identified to meet the challenge of combining these phenomena into scenarios, and consideration has been given to their range of applicability. Although several different approaches can be applied to form scenarios, experience to date indicates that the scenarios selected for detailed assessment will be very similar.

The approach adopted in a particular case will be determined by a range of factors, including the purpose of the assessment, regulatory requirements, available resources, experience, and confidence in the methods used. Scenario development is an interactive and iterative process within the overall safety assessment procedure. Different approaches to scenario development may be used at different stages of a safety assessment programme depending on the level of information and resources available and the immediate goal, e.g. direction of site investigation, determining research priorities. However, for safety assessments in support of licensing applications, a consistent and systematic scenario development procedure must be followed, which should fulfill the need to be both transparent and to provide a high level of confidence that all important safety aspects of the disposal system will be covered by the assessment.

AVANT-PROPOS

La gestion des déchets radioactifs et notamment l'évaluation de la sûreté des systèmes d'évacuation de ce type de déchets jouissent d'une priorité élevée au sein du programme de l'Agence de l'OCDE pour l'Energie Nucléaire. Bien qu'il existe un consensus général dans les pays de l'OCDE en ce qui concerne l'utilisation de dépôts géologiques pour l'évacuation des déchets radioactifs, il est néanmoins nécessaire de procéder à l'analyse de la sûreté à long terme de ces dépôts avant qu'ils ne soient mis en oeuvre, en faisant appel aux techniques d'analyse de performance et à d'autres méthodes. Dans ce contexte, les programmes conduits récemment aux niveaux national et international ont amélioré de façon significative la qualité des méthodes d'évaluation de la sûreté.

Le Groupe Consultatif de l'AEN sur l'Evaluation des Performances des Systèmes d'Evacuation des Déchets Radioactifs (PAAG) a été créé en 1986 dans le but de conseiller le Comité de la Gestion des Déchets Radioactifs sur les aspects techniques de l'évaluation des performances de ces systèmes et de contribuer à la coordination des activités de l'AEN dans ce domaine. Le Groupe Consultatif constitue un forum international au sein duquel les pays Membres examinent et échangent des informations sur des sujets relatifs à l'analyse des performances. Parmi les initiatives du Groupe Consultatif figurent la création de groupes de travail, le patronnage de réunions de spécialistes et de symposia et la préparation d'études sur des questions importantes. L'objectif général du Groupe Consultatif est de contribuer à la mise au point de méthodes et de techniques de haute qualité pour l'évaluation de la sûreté des dépôts de déchets radioactifs, et de promouvoir une utilisation judicieuse et cohérente de ces méthodologies au sein des programmes d'évacuation des déchets radioactifs.

Une des premières actions lancées par le Groupe Consultatif PAAG a été de créer un groupe de travail sur l'identification et la sélection des scénarios à prendre en compte dans les évaluations des performances des dépôts de déchets radioactifs. Le Groupe de travail, dont la composition figure à l'Annexe 1, a procédé à un examen approfondi des méthodes et des expériences relatives à la mise au point de tels scénarios dans les pays de l'OCDE. Le rapport ci-joint du Groupe de travail repose sur une importante bibliographie disponible et fournit un résumé de l'état des connaissances des méthodes permettant la définition de scénarios. Les documents préparés par les membres du Groupe de travail et leur collègues pour présentation et examen lors des réunions ont constitué une source d'informations essentielle à la préparation de ce rapport.

Le présent rapport est publié sous la responsabilité du Secrétaire Général de l'OCDE et n'engage en aucune façon les pays Membres de l'OCDE.

RESUME

Le présent rapport décrit et examine les démarches actuelles en ce qui concerne l'identification et la sélection des scénarios à prendre en compte dans l'analyse de la sûreté des systèmes d'évacuation des déchets radioactifs. Le processus conduisant à la mise au point de scénarios combine des informations sur les caractéristiques du site et des déchets et la compréhension des différents phénomènes intervenant au sein du système d'évacuation, au jugement de scientifiques suffisamment expérimentés et d'autres personnes. Au cours de ce processus, il est important de respecter des procédures strictes et d'établir avec soin une documentation relative à chaque étape, afin de permettre une vérification éventuelle. Il existe un large accord sur la démarche générale à suivre pour l'identification, la classification et le tri des phénomènes qu'il est nécessaire de considérer. Plusieurs démarches ont été avancées pour faire face au défi qui consiste à combiner ces phénomènes dans la construction de scénarios, et leurs domaines d'application ont été examinés. Bien qu'il soit possible d'utiliser plusieurs démarches pour la construction de scénarios, l'expérience actuelle montre que les scénarios choisis pour une évaluation détaillée seront finalement très semblables.

La démarche suivie dans un cas particulier dépendra d'un ensemble de facteurs comprenant l'objectif de l'évaluation, les exigences réglementaires, les ressources disponibles, l'expérience et la confiance dans les méthodes utilisées. La construction de scénarios est un processus interactif et itératif au sein de la procédure générale d'évaluation de la sûreté. Des démarches différentes pour la construction de scénarios peuvent être utilisées à des étapes différentes d'un programme d'évaluation de sûreté, en fonction du niveau des informations et des ressources disponibles et de l'objectif immédiat, par exemple, orientation des recherches sur le site ou détermination des priorités en matière de recherches. Cependant, en ce qui concerne les évaluations de sûreté fournies en soutien des demandes d'autorisation, il convient de suivre une procédure systématique de construction de scénarios, qui devrait nécessairement être à la fois transparente et offrir un niveau de confiance élevé quant à la prise en compte dans l'évaluation de tous les aspects importants de la sûreté du système d'évacuation.

TABLE OF CONTENTS

1. SCENARIO DEVELOPMENT - AN INTRODUCTION

1.1 BACKGROUND

In 1987, on the recommendation of its Performance Assessment Advisory Group (PAAG), the Radioactive Waste Management Committee (RWMC) of NEA established a Working Group to review scenario development techniques used in the performance assessment of nuclear waste disposal. In proposing this initiative, PAAG noted that scenario development is an area of fundamental importance to the comprehensive safety assessment of radioactive waste disposal. PAAG also noted that past approaches could be enhanced by improving the quality assurance, the transparency of the documentation, and by employing a more systematic approach. As the issues related to scenario development methods are common to all disposal concepts, international cooperation was considered particularly appropriate in supporting this effort.

1.2 THE SCOPE AND OBJECTIVE OF THIS REPORT

This report focuses on approaches to scenario development for the post closure performance assessment of land disposal concepts. The report includes methods to identify and select scenarios. Environmental system simulation techniques that may make no explicit use of scenarios are also discussed. Questions pertaining to the actual modelling and consequence analysis of scenarios are not included in this report; discussion of those questions are provided only as far as they directly relate to the identification and selection of scenarios.

A general objective of this report is to present issues related to the identification and selection of scenarios for the performance assessment of radioactive waste disposal. The purpose is to promote consistency in the approaches and methods being used. To meet this objective, the Working Group:

- Reviewed national and international efforts on scenario identification and selection and exchanged information and experiences on approaches and results.

- Identified issues that required special attention and discussion at an international level and discussed them in depth.

- Considered some general guidelines for approaches and methods that could be formulated and agreed upon, and published them in this report.

The purpose of the Working Group effort was not to develop one single approach or method that could then be recommended by NEA to its member countries. Neither was it realistic nor useful for the group to select a list of scenarios for use in safety studies. The primary goal was to increase the understanding of different scenario development methods. The actual detailed application of these methods in safety studies are dependent on the site, the disposal concept, and the purpose of the study; the final approach is therefore a matter for each individual country and organisation to determine.

1.3 THE CONDUCT OF THE STUDY

To collect information on safety assessment studies and scenario development work, a questionnaire was sent to all PAAG members. The responses are summarised and compiled in a NEA scenario catalogue [1]. This catalogue forms a separate annex to this report and was used as background information for the Working Group.

The Scenarios Working Group met three times (1987-89) for information exchange and discussion. Several of the countries represented at the Working Group (Canada, France, Sweden, United Kingdom, and the United States) had already started scenario development programmes. The reporting and discussion of these national scenario development projects at the NEA working group meetings were very valuable and provided the participants with an opportunity to discuss the results and experiences in detail. In addition, a one day topical session on scenarios was held by PAAG in 1988. The progress gained by these efforts has been reported and discussed at PAAG and RWMC meetings and published in two reports [2,3].

Scenario development issues have also been addressed in other parts of the NEA Radioactive Waste Management Programme. Human intrusion scenarios were discussed as part of a workshop on *Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites* which was held in Paris in 1989 [4]. A special session on *Scenario Development and Assessment of Environmental Changes and Disruptive Events* was organised at the International Symposium on Safety Assessment in October 1989 [5]. The NEA work as well as most national scenario related studies were summarised in that session.

1.4 DEFINING SCENARIO AND SCENARIO DEVELOPMENT

Scenarios are used in many fields; economic forecasting, the assessment of technology impact, and military strategic planning are just a few of the applications. The Oxford English Dictionary defines scenario as "a sketch, outline, or description of an imagined situation or sequence of events." In this report, the identification, broad description, and selection of alternative futures relevant to a reliable assessment of the radioactive waste repository safety is termed scenario development. Although a scenario can include uncertainty in present day conditions (e.g. the existence of an undetected fault zone at the disposal site) this report uses the word scenario to denote an alternative future. Thus, a single scenario specifies one possible set of events and processes and provides a broad brush description of their characteristics and sequencing.

1.5 SCENARIO DEVELOPMENT AND SAFETY ASSESSMENT

Safety assessments of some radioactive waste repositories must consider periods lasting thousands of years. Over the course of this period changes due to natural processes and possible human action are expected in the repository and surrounding environment. Since it is impossible to know the future, the related uncertainties must be handled in the safety assessment process; scenario development is the most commonly used technique to account for uncertainties about the future.

A general framework for the conduct of safety assessment is shown in Figure 1. The process starts with scenario development and is followed by model development and

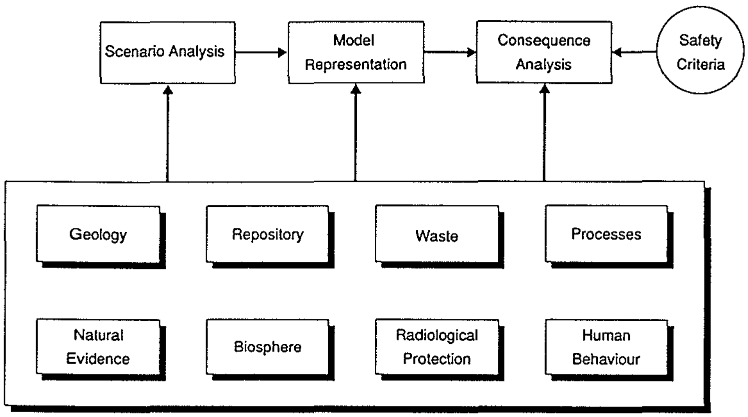


Figure 1: Integrated safety assessments of a disposal system are based upon extensive and systematic use of information from many scientific and technical areas.

consequence analysis. These efforts are supported by a wide range of information on site geology, repository design, the waste characteristics, physical and chemical processes, natural evidence, the biosphere, radiological protection, and human behaviour. There are many links and feedback loops between the safety assessment elements and the information requirements. In particular, the whole safety assessment process requires a number of iterations in order to converge to a consistent result.

Scenario development does not include the use of mathematical or numerical models or the provision of data. The calculations needed for an assessment are considered to be part of the consequence analysis. However, close liaison is needed between those responsible for scenario development, model development, and consequence analysis.

Scenario development is a central part of safety assessment for several reasons. First, scenarios provide the context in which safety analyses are performed. That is, an analysis of the long term safety of a radioactive waste disposal system cannot be conducted without considering future conditions at the site. Second, scenarios influence model development and data collection efforts by identifying which phenomena require examination. Finally, scenarios provide an important area for communication between repository developers, regulators, and others with an interest in repository safety. The communication provides an opportunity to discuss and reach a consensus on areas of specific importance and how best to evaluate their consequences. A direct dialogue between developers and regulators has already been initiated in several countries [6,7]. The partly speculative nature of scenarios, and the relative ease with which they can be described, can provide a rich and accessible means for public involvement.

1.6 THE DESIGN AND CONTENTS OF THE REPORT

Chapter 2 presents a brief overview of some aspects of safety assessment approaches. It is intended to provide an understanding of both the general considerations affecting the safety assessment task and its use in the development of repository programmes. Chapter 3 contains a brief discussion of the theoretical and practical aspects related to conceptualizing and representing "the real world" (or selected natural and man made systems within the real world, e.g. radioactive waste repositories)by a model or set of models. The identification, classification and screening of phenomena which could affect repository safety are considered in Chapter 4. Chapter 5 reviews experience in the development and application of scenario techniques. The approaches to the difficult problem of organising phenomena that has been identified as relevant for safety into a framework for consequence analysis (formation of scenarios), are considered in Chapter 6. The use of environmental simulation techniques in particular to aid in or to supplement scenario development is discussed in Chapter 7. Finally, Chapter 8 offers some general observations and conclusions regarding scenario development and the outlook for future progress.

2. THE SAFETY ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL SYSTEMS

This chapter provides background information on the purpose, approach, and roles of safety assessment methods. It is intended to provide an understanding of both the general considerations affecting the safety assessment task and its use in the development of repository programmes. A more extensive discussion of safety assessment methods can be found in the NEA Report *Review of Safety Assessment Methods*, which forms the basis for this chapter [8].

2.1 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 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. 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 occurrence.

- 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.

2.2 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. For example: 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; and the components and behaviour of systems to seal underground openings made during repository characterisation and development require study. The performance assessment team must be multi-disciplinary in order to be able to assimilate and assess these various inputs and collect and organise the information in an appropriate format for the 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 iterative 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.

Estimates of long-term system or subsystem performance are normally considered as indicators of system performance cr 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 of performance assessments. Such techniques are necessary to allow disposal sites to be licensed using these assessments and other tools.

2.3 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 of performance assessment applications is shown in Figure 2. 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.

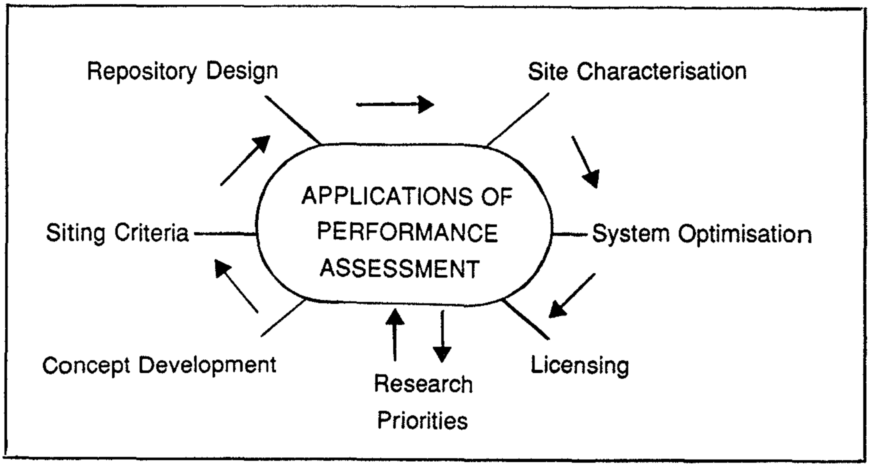


Figure 2: Performance assessment plays an important role throughout the development of repository programmes [8].

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 Stockage de l'Aube. In the United States, a deep repository is under development in a salt formation in New Mexico; this facility, the Waste Isolation Pilot Plant, is intended for alpha-bearing wastes from the United States 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.

2.4 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. It is not possible to estimate the probability of many of these cases 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. THE REAL WORLD AND LEVELS OF REPRESENTATION

This chapter contains a brief discussion of the theoretical and practical aspects related to conceptualizing and representing "the real world" by a model or set of models (or selected natural and man made systems within the real world, e.g. radioactive waste repositories). For this purpose the use of scenarios is illustrated.

3.1 THE DESCRIPTION AND MODELLING OF REAL-WORLD SYSTEMS

In theory, at any moment in time, a description of the world can be made in terms of the general features present and their detailed characteristics. On a much smaller scale, a similar description can be developed that represents a radioactive waste disposal system. Building a single model which combines and represents the important phenomena and their interactions at an appropriate level of detail is a complex process. As time progresses, phenomena (processes and events) act to modify the characteristics of the system, its environment, and the radiological features. To build the model, the phenomena and their interactions must be identified and realistic models of the individual and related phenomena must be developed. The models describing the evolution of the repository, the natural environment, and radiological features must also be combined or linked in an appropriate way.

For safety assessments concerned with radioactive waste disposal a distinction can be made between the radiological features, e.g. the radionuclide distribution and flux, and the repository and natural features where the radiological features exist. Although this is an artificial distinction, it is useful in determining the best way to represent the disposal system. As increasingly complex models are developed they will require large amounts of computer processing time; it is important to verify that model simplifications adopted to meet computing constraints do not degrade the representation of critical processes.

3.2 THE USE OF SCENARIOS TO REPRESENT SELECTED ASPECTS OF A SYSTEM

An alternative to a single system simulation model, is to use detailed, individual models to represent individual aspects of the repository and natural environment. The results of these models and judgements can then be combined to construct a set of future environments, i.e. scenarios, that span the set of possible futures. In practice this will be an iterative process in which the results from one model are used to modify inputs to another until consistent and compatible descriptions of the different aspects of the environment and their evolution under certain external constraints are developed. This process can generate quantitative descriptions of scenarios and derive parameter values and distributions which can then be used as input to the radiological assessment model or models. This is illustrated in Figure 3.

One advantage of this procedure is that a qualitative approach can be adopted at an early stage and be used to guide further work. By considering the features of the repository and natural environment, and the phenomena which act on them, experts are able to estimate the possible changes to the repository and natural environment and thus define preliminary qualitative scenarios. These can be used to guide further investigations using process models.

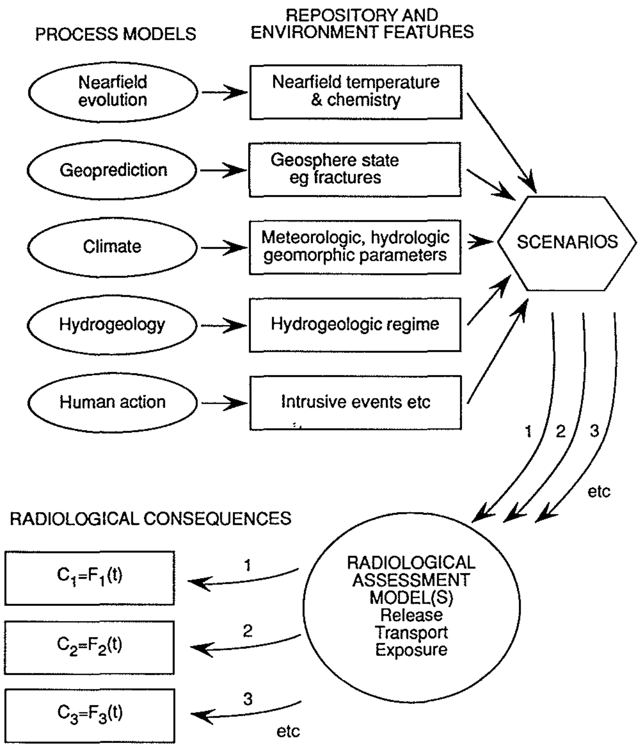


Figure 3: Schematic diagram of the use of scenarios to represent the disposal system. Based on knowledge and detailed modelling of the features of the repository, natural environment and their evolution, scenarios are developed (using a systematic procedure and human judgement) for which release, transport and exposure modelling is performed to yield potential radiological consequences (C_i) as a function of time (F_i (t)).

It is clear from Figure 3 that independent estimates of consequences can be produced for each scenario. Results for individual scenarios may be given as "what if..." results; this may be appropriate where criteria are non-probabilistic or more generally for very unlikely scenarios, i.e. if the probability of occurrence within the time scale of assessment is very small. However, if probabilistic criteria are used, the aim should be to assign coherent probabilities to scenarios so that the results can be combined. See Figure 4.

Scenarios should be regarded as stylised representative futures which, when summed, span the variety of possible futures. It is therefore important that the range of scenarios adopted is sufficiently broad. Depending on the details of national regulations and licensing procedures the probability density function (pdf) of the potential consequences may be the important entity. This is the case if an overall risk criterion is used. In other cases the results of each individual scenario may be judged separately against the safety criteria. This is the case when dose-limit criteria are used in conjunction with broad judgement of individual scenario probabilities. Figure 5 summarises the role of scenarios and illustrates the use of the integrated simulation and scenario approaches.

Although phenomena provide the driving force for change in the environment, scenarios are most naturally defined in terms of effects, that is the system state or its time history. This is important when considering the completeness of the scenario set. The set must span all possible states or evolutions of the environment that could significantly influence disposal safety.

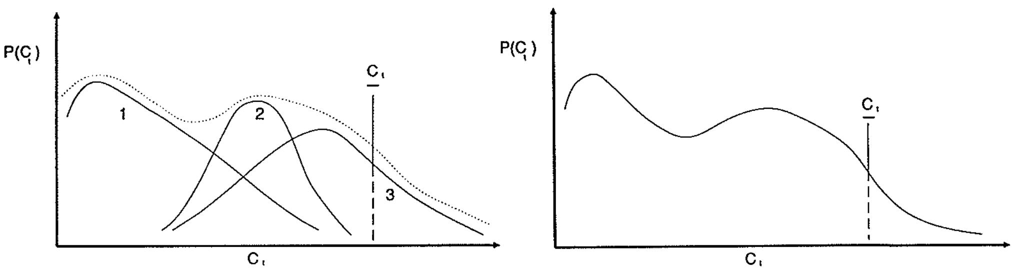


Figure 4: The probability density function of radiological consequence parameter C_t at representative time, t, can be obtained either from system simulation modelling as shown on the left or modelling of separate scenarios as shown on the right. C_t is a measure of the radiological consequence (at time t) and $P(C_t)$ is the probability density function.

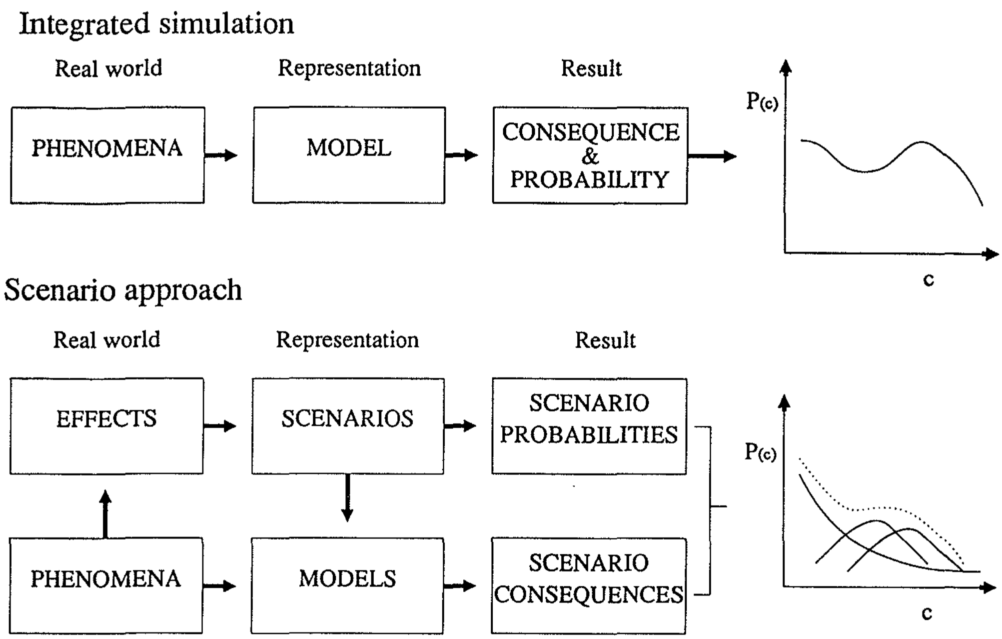


Figure 5: Illustration of the role of scenarios. Multiple scenarios and models are needed where it is not possible or convenient to describe the system using a single integrated model.

4. THE IDENTIFICATION, CLASSIFICATION, AND SCREENING OF PHENOMENA

The first step in scenario development is the compilation of a catalogue of phenomena that can affect repository safety. To generate a sufficiently extensive list, this process must be free of limitations and draw on the imagination and experience of a wide range of people. At the same time the list must be comprehensive, traceable, and well documented; this requires the process to have a basic structure. To balance these requirements, it is helpful to divide the phenomena selection process into three sub tasks: identification, classification, and screening. The general procedure discussed in this chapter is based on the work done by Sandia National Laboratories for the US Nuclear Regulatory Commission [9,10,11,12]. The procedure is illustrated in Figure 6.

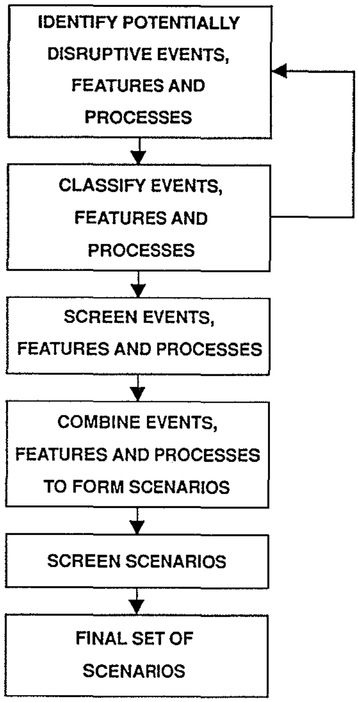


Figure 6: Graphical illustration of scenario selection procedure. The first three steps are discussed in Chapter 4 and the following in Chapter 6.

4.1 THE IDENTIFICATION OF FACTORS

The first step in the phenomena selection process is the identification of a comprehensive list of factors commonly known as features, events, and processes (FEPs). Several years ago the IAEA compiled a list of FEPs that has provided a useful starting point for additional efforts in this area. Box 1 contains an example catalogue of FEPs mainly relevant to a deep geological repository at a hard rock site. However, it includes FEPs that are relevant to other types of formations (clay, sedimentary, salt) as well.

To be thorough, the identification stage needs to include all phenomena that could affect repository safety. For example, there should be no time cut-off during this step, even if regulatory guidelines recommend it. Comprehensiveness is required at this initial stage so that interactions are not overlooked; inappropriate phenomena can be discarded in later parts of the procedure.

To obtain a full spectrum of perspectives, input is needed from each part of the safety assessment process. Specialists from relevant disciplines, such as physics, chemistry, geology, civil engineering, should also be involved. A variety of methods can be envisaged for using these people. In some cases it may be advantageous to have an expert panel formulate an initial list and then to have this reviewed by those outside the immediate field. Time must be allotted to allow feedback and iteration with other parts of the scenario development procedure.

Unconscious screening due to prejudice or unimaginative participants can be alleviated by drawing on people with a wide range of expertise and interests, and by using formal elicitation techniques. A formal expert judgement process has a predetermined structure for the collection, processing, and documentation of expert's knowledge. The process of eliciting expert judgement consists of four basic steps [13]: (1) the identification of issues to be addressed by the experts; (2) the selection of experts; (3) pre-elicitation training of experts; and (4) elicitation of judgements.

While expert judgement plays a crucial role in the identification step, it is also possible to introduce practical aspects into the proceedings. This can be done by examining natural and historical evidence from systems which bear resemblance to some aspect of a repository and its surroundings. For example, uranium ore bodies and geochemical anomalies can provide clues to the events and processes that affect radionuclide migration over geological time scales. Archaeological evidence can also provide insights into phenomena occurring in time scales spanning hundreds to thousands of years.

When compiling a list of FEPs, it is important to consider both the phenomena that are amenable to scientific investigation, e.g., climate and geological change, and the direct or indirect effects on the disposal system due to future human action.

Box 1. Example compilation of features, events, and processes for a deep geological repository.

1. NATURAL PHENOMENA

1.1 EXTRA TERRESTRIAL
1.1.1 Meteorite Impact
1.1.2 Solar insolation

1.2 GEOLOGICAL
1.2.1 Plate movement/ tectonic change
1.2.2 Changes in the Earth's magnetic field
1.2.3 Magmatic activity (intrusive, extrusive)
1.2.4 Metamorphic activity
1.2.5 Diagenesis
1.2.6 Uplift and subsidence (orogenic, isostatic)
1.2.7 Diapirism
1.2.8 Seismicity
1.2.9 Fault activation
1.2.10 Fault generation
1.2.11 Rock heterogeneity (permeability, mineralogy), affecting water and gas flow
1.2.12 Undetected features (faults, fracture networks, shear zones, brecciation, gas pockets)
1.2.13 Natural gas intrusion

1.3 CLIMATOLOGICAL
1.3.1 Precipitation, temperature, and soil water balance
1.3.2 Extremes of precipitation, snow melt and associated flooding
1.3.3 Coastal surge, storms, and hurricanes
1.3.4 Sea-level rise/fall
1.3.5 Periglacial effects (permafrost, high seasonality)
1.3.6 Glaciation (erosion/ deposition, glacial loading, hydrogeological change)
1.3.7 No ice age

1.4 GEOMORPHOLOGICAL
1.4.1 Land slide
1.4.2 Denudation (aeolian and fluvial)
1.4.3 River, stream, channel erosion (downcutting)
1.4.4 River meander
1.4.5 Freshwater sediment transport and deposition
1.4.6 Coastal erosion and estuarine development
1.4.7 Marine sediment transport and deposition
1.4.8 River meander
1.4.9 Chemical denudation and weathering
1.4.10 Frost weathering

1.5 HYDROLOGICAL
1.5.1 River flow and lake level changes
1.5.2 Site flooding
1.5.3 Recharge to groundwater
1.5.4 Groundwater discharge (to surface water, springs, soils, wells, and marine)
1.5.5 Groundwater flow (Darcy, non-Darcy, intergranular fracture, channelling and preferential pathways)
1.5.6 Groundwater conditions (saturated/ unsaturated)
1.5.7 Saline or freshwater intrusion
1.5.8 Effects at saline-freshwater interface
1.5.9 Natural thermal effects

1.6 TRANSPORT AND 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 (linear/non-linear, reversible/irreversible)
1.6.8 Dissolution, precipitation, and crystalisation
1.6.9 Colloid formation, dissolution, and transport
1.6.10 Complexing agents
1.6.11 Fracture mineralisation and weathering
1.6.12 Accumulation in soils and organic debris
1.6.13 Mass, isotopic and species dilution
1.6.14 Chemical gradients (electrochemical effects and osmosis)

1.7 ECOLOGICAL
1.7.1 Plant uptake
1.7.2 Animal uptake
1.7.3 Uptake by deep rooting species
1.7.4 Soil and sediment bioturbation
1.7.5 Pedogenesis
1.7.6 Chemical transformations
1.7.7 Microbial interactions
1.7.8 Ecological change (e.g., forest fire cycles)
1.7.9 Ecological response to climate (e.g., desert formation)
1.7.10 Plant and animal evolution

2. HUMAN ACTIVITIES

2.1 DESIGN AND CONSTRUCTION
2.1.1 Undetected past intrusions (boreholes, mining)
2.1.2 Investigation borehole seal failure and degradation

2.1.3 Shaft or access tunnel seal failure and degradation
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 failure)
2.1.7 Common cause failures
2.1.8 Poor quality construction
2.1.9 Design modification
2.1.10 Thermal effects (concrete hydration)

2.2 OPERATION AND CLOSURE
2.2.1 Radioactive waste disposal error
2.2.2 Inadequate backfill or compaction voidage
2.2.3 Co-disposal of reactive wastes (deliberate)
2.2.4 Inadvertent inclusion of undesirable materials
2.2.5 Heterogeneity of waste forms (chemical, physical)
2.2.6 Accidents during operation
2.2.7 Sabotage
2.2.8 Repository flooding during operation
2.2.9 Abandonment of unsealed repository
2.2.10 Poor closure
2.2.11 Post-closure monitoring
2.2.12 Effects of phased operation

2.3 POST-CLOSURE SUB SURFACE ACTIVITIES (INTRUSION)
2.3.1 Recovery of repository materials
2.3.2 Malicious intrusion (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

2.4 POST-CLOSURE SURFACE ACTIVITIES
2.4.1 Loss of records
2.4.2 Dams and reservoirs, built/drained
2.4.3 Rivers rechanneled
2.4.4 Irrigation
2.4.5 Altered soil or surface water chemistry
2.4.6 Land use changes
2.4.7 Agricultural and fisheries practice changes
2.4.8 Demographic change, urban development
2.4.9 Anthropogenic climate change (greenhouse effect)
2.4.10 Quarrying, near surface extraction

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 aperture changes
3.1.4 Induced hydrological changes (fluid pressure, density convection, viscosity)
3.1.5 Induced chemical changes (solubility, sorption, species equilibrium, mineralisation)

3.2 CHEMICAL
3.2.1 Metallic corrosion (pitting/uniform, internal and external agents, gas generation e.g. H_2)
3.2.2 Interactions of host materials and groundwater with repository material (e.g., concrete carbonation, sulphate attack)
3.2.3 Interactions of waste and repository materials with host materials (electrochemical, corrosive agents)
3.2.4 Non-radioactive solute plume in geosphere (effect on redox, pH, and sorption)
3.2.5 Cellulosic degradation
3.2.6 Introduced complexing agents and cellulosics
3.2.7 Microbiological (effects on corrosion/ degradation, solubility/ complexation, gas generation, e.g. CH_4CO_2)

3.3 MECHANICAL
3.3.1 Canister or container movement
3.3.2 Changes in in-situ stress field
3.3.3 Embrittlement and cracking
3.3.4 Subsidence/collapse
3.3.5 Fracturing
3.3.6 Gas effects (pressurisation, disruption, explosion, fire)

3.4 RADIOLOGICAL
3.4.1 Radiolysis
3.4.2 Material property changes
3.4.3 Nuclear criticality
3.4.4 Radioactive decay and ingrowth (chain decay)

4.2 CLASSIFICATION OF FEATURES, EVENTS, AND PROCESSES

The identification process is followed by, and closely linked to the classification step. By classifying features, events, and processes under different schemes, information on additional phenomena and interaction can be gained. It is important to demonstrate that a sufficiently comprehensive list has been compiled; this is a critical aspect of scenario development and lays the foundation for the overall performance assessment effort. In addition, classification under certain headings, such as release, transport and exposure phenomena, provide a framework for organising the scenario development exercise and the subsequent assessment. The primary objective is to uncover missing factors, therefore classification schemes that examine the system from different viewpoints should be used. Examples of classification schemes which provide alternative perspectives of future system behaviour are discussed below.

Natural, Human, and Repository

Classifying factors according to their cause, i.e., naturally occurring, the result of human activities, or factors that arise from effects due to the repository or waste is a standard approach and was used in the IAEA list. To take a more detailed view these classes can be divided further. For example, natural phenomena can be grouped under headings such as celestial bodies, surficial phenomena, and subsurface phenomena. In a similar manner, human induced effects could be grouped according to causes such as inadvertent intrusion, undetected features, and hydrological stress.

Time Scales

Classification according to the time scale during which different events and processes occur can be useful in assessing their relevance for safety assessment and in determining the level of detail necessary. For example, short term (100 years), medium term (10,000 years) and long term (1,000,000 years) categories could be used. There are primarily two time periods of interest. The first is the time between repository closure and the event or process having a reasonable probability of being initiated, or simply, the typical time between events. The second is the time over which an event or process takes place. From this information, the likelihood of events and processes occurring simultaneously can be estimated.

Near Field, Far Field, and Biosphere

A useful scheme, especially from a groundwater migration view, is to classify phenomena by the location in which they might occur. One scheme might be divided into the near field which immediately surrounds the repository, the undisturbed geology or far field, and the biosphere. Initially, all processes which could occur should be listed regardless of whether they could affect radionuclide mobility on their own, since interaction with other phenomena could lead to such effects. Phenomena occurring at the near field/far field, and far field/biosphere interfaces should also be considered. Thus these could be added as two additional categories in this classification.

Probability and Consequence

This approach categorises phenomena into four areas according to the magnitude of the probability and the consequence. The approach can also be useful in a presentational context as shown in Figure 7.

Scientific Discipline

An alternative perspective is provided by classification according to scientific discipline such as physics, chemistry, biology, geology, civil engineering, anthropology, etc.

	PROBABILITY	
CONSEQUENCES	Large	Small
Large	1. To be avoided by repository design and concept	2. Quantitative discussion
Small	3. Quantitative consequence analysis	4. Qualitative discussion

Figure 7: Simple diagram of possible combinations of probabilities and consequences of phenomena (on scenarios) and how they can be considered in an assessment [14].

Radionuclide Transfer Agent

The factors can also be classified by the radionuclide transfer agent. The transfer agent most often considered, at least for near field and far field transport is groundwater. This category can be further divided into radionuclides that are transferred in soluble and colloidal forms. Another radionuclide transfer agent is gas. Gas can be divided in a similar fashion into radioactive gases and aerosols. In addition to groundwater and gas, radionuclides can be transferred by erosion, tectonics, and diaparism or by people, animal, and plants. The latter cases are important if the radionuclides are able to enter the biosphere.

Direct and Indirect Release to the Biosphere

Direct releases to the biosphere can result from such processes as human intrusion or natural disruptive events which bypass the geological barrier. Indirect release can occur when contaminated groundwater migrates from the repository through the geosphere and discharges into shallow groundwater or lake sediment.

Release, Transport, and Exposure

One other method of classification is accomplished according to release, transport, and exposure phenomena. Release phenomena are those that directly affect the escape of radionuclides from an underground facility such as the formation of complexing ions in the repository from organic degradation. Transport phenomena affect the migration of radionuclides if they escape the repository. An example of changing transport phenomena might be the closure of a fracture pathway due to mineralisation. Exposure phenomena affect the transfer of radionuclides from biosphere receptors to people. An example of this is the inhalation of suspended dust from contaminated land.

4.3 SCREENING OF FEATURES, EVENTS, AND PROCESSES

The result of the identification and classification stages is to produce a large number of features, events, and processes which may affect disposal system safety. After analysis, many of these FEPs will be found to be irrelevant to the safety assessment of a particular repository or site. Thus these factors can be screened using well defined and justifiable criteria. This process serves to reduce the amount of detailed analysis required at later stages in the assessment.

Rejection of phenomena should be done in a transparent and documented way. In general, detailed consequence analysis should be avoided at this stage. However, there may be a need to perform simple calculations, such as bounding estimates. If so, the assumptions and data used should be clearly stated. These guidelines are important since an assessment is only as strong as its weakest link, and there is potential for much effort to be wasted analysing the consequences of scenarios which are not important.

The screening process is not only site and system specific, it must meet the applicable disposal regulations. At this stage, phenomena are considered one by one, but are checked for interaction with other phenomena. If there are questions concerning the screening of a factor at this stage it should be retained. The factor can always be reevaluated at a later scenario screening step. Examples of screening criteria that can be used at this step are discussed below.

Physical Reasonableness

A number of phenomena in a comprehensive list of features, events, and processes cannot occur at a particular repository system and site. For example, dissolution cavities cannot occur in crystalline rock. Those phenomena which are clearly not applicable to the specific repository or site can be eliminated from consideration.

Regulations

The importance of regulatory criteria will vary from country to country. For example, if the pertinent regulations require quantitative analyses using predictive models that cover 10,000 years, then only phenomena which occur beyond this time can be excluded. A time cut off can also be imposed for non-regulatory reasons. It may still be necessary to make reasonable arguments, even if they are non-quantitative, about expected system behaviour for the longer time periods when predictive models are not used.

Probability

Some events, features, and processes will have very low probabilities of occurrence during the time period of concern, or equivalently a very low average frequency over that period. To screen out such phenomena, it is necessary to define a cut off probability or frequency which is consistent with national regulations, although perhaps allowing an extra margin of safety. For example, according to the environmental standard used by the United States Environmental Protection Agency events and processes with a probability of less than 1 in 100,000 over 10,000 years do not need to be considered [15]. As previously mentioned, probabilities are very difficult to set. Thus, if there is doubt that a phenomena satisfies the criteria it should be retained.

Effects on Repository and Site

At this stage in the scenario development procedure, it is not recommended that phenomena be excluded on the basis of their potential radiological consequences unless this can be done by a simple bounding analysis. However, they can be excluded by virtue of their relatively minor effect on the repository system or site. For example, if a phenomenon affects the hydrogeological characteristics of a site, but only by an amount less than a competing process or the general uncertainty in parameter values, it should be discarded. The assumptions, data, and results of such estimates should be documented.

4.4 EXPERIENCE WITH FEATURES, EVENTS, AND PROCESSES

Many countries have extensive experience in identifying, screening, and selecting FEPs. This experience has resulted in a consensus on the need and usefulness of performing these initial steps of the scenario development procedure. That is, whatever approach one intends to use for scenario formation there is a need for a screened list of factors that should be considered further. Historically, attention has been focused on FEPs related to groundwater migration. However, in recent years, FEPs related to human actions, gaseous migration, and the effects of environmental change have also been systematically identified. This is because they too need to be considered in appropriate detail.

Initial lists of FEPs before classification and screening can be fairly extensive. For example the Canadian effort initially identified more than 1,000 factors [16]. A substantial amount of work is needed to sort, classify, and screen such lists. This can be done in many ways using different sorting and classification schemes as illustrated above. Since different people and expertise are involved, the initial list will be a mixture of loosely defined factors at different levels of detail. Therefore it is necessary to define the FEPs in more detail, to sort out inconsistencies and eliminate overlap between different FEPs, and to structure or categorise them in a way that facilitates systematic consideration in scenario formation and performance assessment.

One method to process FEPs in great detail was developed in Sweden. The Swedish programme established a database that: documents the FEPs identified, provides the ability to sort and search FEPs, houses a referencing system, enables continuous update, and provides systematic documentation of all decisions that concern the classification, and screening of FEPs [17]. The main feature of this data base is called a memo comment. A memo comment is prepared for each FEP and contains a description of the classification and screening process. Examples of memo comments are shown in Boxes 2A and 2B. Although time consuming, memo comments are valuable tools that can provide the systematic documentation needed to trace the considerations made in a scenario study. In addition, the system can facilitate communication and understanding between the different experts involved in a safety study and its review.

Box 2A. A few selected examples of FEPs and their memo comments [17].

1.1.1 CRITICALITY

Screening-OUT

PROCESS
Plutonium criticality could theoretically occur within the canister during the first 50,000 years of storage. This would call for selective dissolution and transport of uranium and part of the canister filling material. Uranium criticality could only occur outside the canisters. This would call for selective deposition of dissolved uranium in the bentonite. A minimum amount of 4,400 kg of uranium is necessary for criticality. The consequences have been calculated to be insignificant, max 130kW power in one tunnel.

EFFECTS
Criticality would impact the radionuclide inventory and thermal behaviour of the repository, i.e. the near field models. The far field and biosphere models would not be influenced, only some input data of nuclides and thermal impact.

REFERENCES
The case has been studied in the KBS-2 study by ASEA-ATOM. Reference to KBS-2, volume 2, page 255 and KBS Technical Report 108, "Criticality in a spent fuel repository in wet crystalline rock", 1978-05-30.

SCREENING
According to the reference reports, the case could be screened out. The possible thermal heat produced is restricted, as the increase in fission product inventory. The probability is also shown to be very low, although the phenomena cannot be ruled out.

5.46 GROUNDWATER RECHARGE-DISCHARGE

Screening-OUT (ADM)

This is a heading for a primary FEP and is thus screened out on the ADM criteria.

5.22 ACCUMULATION OF GASES UNDER PERMAFROST

Lumping 5.17, Screening- KEPT

PROCESS
Gases from deeper geological layers might accumulate in the repository during permafrost, especially during the early phase when the nearby rock is still kept at higher temperatures.

CAUSES
Nitrogen and light hydrocarbons, notably methane, are known to penetrate from deep geological formations to the surface.

EFFECTS
Gas accumulation will lead to enforced outflow of groundwater from the repository. This will take place at a very slow rate, and the consequence must be regarded as negligible. The influence of a gas cushion on the flow field might be of some importance, however.

Clathrates are methane hydrates that occur as solids in certain conditions of temperature and pressure and are also associated with permafrost. They are found underground e.g. in the Spitzbergen, in sediment areas with methane production and in the seabed at greater depth. Their potential role can be included within the general framework of gas production in the repository, its effect on migration, or on explosion in connection with radiolytic gases. As a result of the heating by the waste, existing clathrates could produce methane.

Note that their presence is extremely difficult to detect since solid samples are sublimated when brought to room temperature and pressure. However, crystalline rocks are not known to contain large amounts of methane. However, for an intermediate level repository methane generation can be a problem and the potential formation of clathrates should be considered. This issue needs to be carefully considered and documented, but probably not included in the initial list of scenarios.

Box 2B. A few selected examples of FEPs and their memo comments [17].

5.45 COLLOID GENERATION AND TRANSPORT

Screening-PROCESS SYSTEM

DESCRIPTION
Colloids are particles in the size range between 1 and 100 nm. They might absorb or otherwise include radionuclides in the groundwater system.

CAUSES
Colloids are always present in deep groundwater; measured concentrations are generally less than 1 mg/l. They are of both inorganic and organic origin. Possible sources of specific significance for a deep geological repository in crystalline rock are the presence of gradients in groundwater composition leading to precipitation (e.g. as a result of changes in redox potential and pH), and erosion (dispersion) of clay minerals. Under extreme external conditions (e.g. glaciation, faulting) transients in colloid concentration might occur.

EFFECTS
Depending on composition and physio-chemical characteristics (e.g. size distribution, surface potential, etc.) colloids are transported more or less with the same velocity as the groundwater. Reversible sorption of radionuclides on particles in the larger size range (the formation of such colloids should be reversible and sorption of them considerable). "Irreversible" sorption on and transport with colloids in the intermediate range might be of some importance for certain radionuclides. Until this problem has been further studied these statements are to be regarded as speculations, however.

5.17 PERMAFROST

Screening-KEPT

PROCESS
There are lot of evidences that Sweden has gone through several cycles of permafrost during the quartenary period (last 2 million years). At present, in the Spitzberg areas, the permafrost depth is 450 m, and in Siberia, depths exceeding 1500 m have been reported. Although these latter examples are possibly permafrost of older ages than the last ice age. With today's present knowledge however it is not possible to exclude a deep permafrost situation in Sweden. It is therefore necessary to consider the potential of permafrost as repository depth as well as on the surface.

In a gross generalization it is assumed that the limit of permafrost shows a strong relationship to the mean annual air temperature isotherm of -1 to -2 degrees C. The depth of frost penetration is affected by the topography and the thickness of the snow cover. The geothermal gradient is in general in Sweden today in crystalline rock about 3 degrees C per 100 m with some local variations. This is also a controlling factor, the lower limit to permafrost approaches an equilibrium depth, at which the temperature increase due to earth heat just offsets the amount by which the freezing point exceeds the mean surface temperature.

EFFECT
Possible potential effects of permafrost are for instance fracturing or opening of fractures because of water freezing; compression of backfill and opening of voids at melting; increasing water flow in the temperature gradient and potential rapid flow paths; accumulation (concentration) of gas and radionuclides below the lower surface of the permafrost frozen rock mass giving rise to a pulse of radionuclides when melting occurs.

5. SCENARIO CONSTRUCTION - AN OVERVIEW OF PAST EXPERIENCE

Scenario development for radioactive waste disposal systems is strongly linked to the safety assessment studies of such systems. This chapter discusses the techniques used to develop scenarios during the last twenty years.

5.1 THE DEVELOPMENT OF SAFETY ASSESSMENT FOR RADIOACTIVE WASTE DISPOSAL SYSTEMS

Assessments of the feasibility and safety of nuclear waste disposal in geological formations first appeared in the 1950s [18]. During the last ten years a considerable number of comprehensive, long term safety assessments of well defined, nuclear waste disposal systems have been performed. While the early assessments were performed on a generic basis with only sparse data on the characteristics of the proposed geological formation, today's studies are primarily site specific and are supported by comprehensive data bases.

Improvements to the safety assessment process include increasingly complex and realistic models, and enhanced systematic methods to describe uncertainties in the results. There has been rapid progress in the modelling of hydrology, geochemistry, and radionuclide migration. Until just a few years ago, most safety studies did not include an explicit and well documented phase that identified and selected factors that could influence the long term safety of the assessed system. Now this process is an important part of all safety assessments.

5.2 AN OVERVIEW OF SCENARIO DEVELOPMENT METHODS

In a simple manner, scenario development might be described as a systematic focussing of assessment work on the conditions and phenomena (scenarios) that are most important to the performance or safety of the repository system. If the scenario development is correct the safety assessment will cover the long term safety aspects of the disposal system. The scenario development methods that have been applied in safety assessments can, for discussion purposes, be grouped into the following classes:

1. Judgemental
2. Fault or event tree analysis
3. Systematic

In the judgemental method, the assessment team or invited experts select the phenomena or conditions that they believe are most important, and define possible release situations, without a systematic attempt to identify or examine all phenomena or conditions. The reasoning underlying the selection may or may not be formally recorded. The judgmental method has been used in the vast majority of the safety assessments reported to date [14,19,20,21,22].

The fault or event tree method is a traditional technique of risk analysis quite often 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 event combinations are then evaluated by various screening techniques to determine high risk scenarios. Although literature reports of the use of fault or event tree analysis for geological isolation of radioactive waste are minimal it has undoubtedly aided analyses reported using the judgmental format [23,24,25,26,27].

The systematic approach is used to denote methods that are based on work accomplished at Sandia National Laboratory in the early 1980 and is discussed in Chapter 6 [9]. This work was later applied and enhanced in the United States, Canada, Sweden, and the United Kingdom [5,16,28]. The systematic approach uses a comprehensive initial phase to identify factors (features, events, and processes) that can influence repository safety directly or indirectly. The approach also uses a structured and well documented procedure for selecting and combining these factors into scenarios for detailed modelling.

A fourth method that includes handling FEPs, the system simulation approach, is discussed in Chapter 7. This method can be viewed as an alternative to the use of scenario approaches, although the stages of phenomena elicitation and screening are necessary initial activities both in the system simulation and scenario approaches. The system simulation approach aims to develop and uses a model of the environment and repository system to simulate the behaviour of the isolation system and the surrounding environment over time. Although the approach starts with the identification and selection of the phenomena to be considered, the phenomena are not explicitly combined into scenarios. Instead they are included and combined into the overall system model which is used for consequence analysis. A full assessment application using this method has not yet been done, but attempts to develop the method were first made ten years ago in the United States [29,30]. The most recent developments have been made in the United Kingdom [31,32]. A full trial of the methodology for a hypothetical deep underground repository at a real site in the United Kingdom has recently been completed [33].

It should be noted that all these methods, when applied, have a lot in common. They may be viewed as different ways to organise, evaluate, and present the information available on nuclear waste isolation systems and relevant processes, and to take account of the large uncertainty in the future state of the repository and environment.

5.3 THE APPLICATION OF SCENARIO DEVELOPMENT IN SAFETY ASSESSMENT

5.3.1 Safety Developments using the Judgmental Approach

Most published safety assessments of nuclear waste disposal systems have used judgmental methods to select scenarios for detailed assessment [1]. Safety studies have been wide ranging in the documentation and discussion of the procedure used and the criteria for the identification and selection of factors and scenarios. The differences can be partly explained by the wide variety of reasons for conducting the studies; the reasons ranged from method development and scoping and feasibility studies, to full licensing for the construction and operation of a repository.

In the past, only a limited number of formal requirements were required to demonstrate comprehensiveness. As a result, the factors included in the formulation of safety studies (i.e., scenario selection) were quite varied. The safety assessment task often advanced to modelling and consequence calculations after a fairly rapid scenario screening effort. This less than systematic approach did not sufficiently document why many factors, explicitly or implicitly, were screened out. Although this may have been a correct use of the limited resources at the time, assessments are now being prepared for actual sites which must be able to withstand detailed scrutiny by the regulatory authorities and public. For such assessments, the importance of comprehensiveness and traceability in both the assessment and documentation is increased.

A few of the safety assessments based on the judgmental scenario approach are presented in Boxes 3A and 3B. These studies are highlighted because they have had to comply with formal regulatory procedures for either concept assessment, licensing for construction, or the operation of a disposal facility. The studies presented vary in the degree to which they discuss the criteria for, and elimination of, scenarios from consideration. A list of phenomena presented in an IAEA publication in 1981 has been used as a starting point in many of the safety assessments using judgmental scenario development [34]. In those cases now being updated, there is a shift to more formal and rigorous scenario development procedures that are labeled systematic in this report.

5.3.2 Scenario Development using the Fault or Event Tree Approach

Event tree techniques have been used in several radioactive waste disposal safety studies. These techniques have been used as part of the systematic approach developed by Sandia National Laboratories for assessments of potential repositories in salt, basalt, and tuff in the United States [23,24,25,26,36]. A safety assessment study of a repository in clay (Belgium) has also been conducted using event tree techniques [27]. See Figure 8. These studies were performed five to ten years ago.

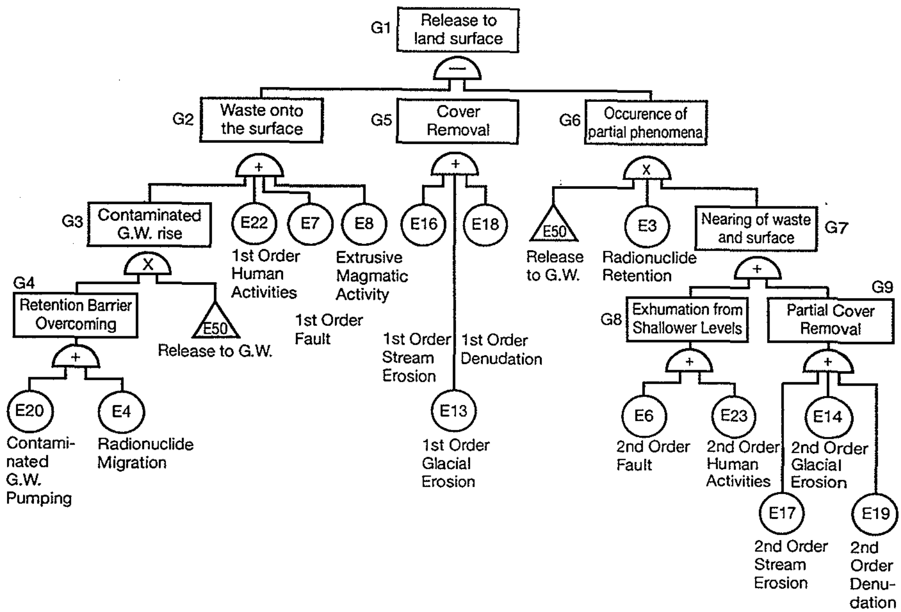
Box 3A. Safety Studies based on the Judgemental Approach to Scenario Development (KBS-3 and Gewahr)

Safety Study and Purpose	Scenario Analysis Approach
KBS-3: Study of the feasibility and safety of spent fuel disposal in crystalline rock in Sweden [22] **Remarks** The choice of scenarios in KBS-3 was not particularly criticized in the review process. A more comprehensive and systematic approach to scenario development is foreseen in the upcoming SKB-91 safety study.	Judgement. A most probable scenario was described in words. A set of base case groundwater intrusion scenarios with conservative assumptions were modelled in detail with either a well, lake, sea, or peatbog recipient. The effects of continued land rise was also discussed. The following accident and event scenarios were treated qualitatively: earthquake - rock displacement, meteorite impact, criticality in the repository (probability discussed and consequences quantified), and human intrusion. Some bounding scenarios (initial canister failure, oxidized geosphere, high colloid transport fraction) with highly conservative assumptions about the canister or the geopshere barrier were also assessed quantitatively.
Gewähr Project: Study of the feasibility of safe HLW disposal in crystalline rock in Switzerland. [14] **Remarks** The Gewähr study represents one of the more systematic judgemental scenario analysis reported. Several other studies reference the Gewahr listing and classification of factors.	Expert Group Judgement. A list of factors were established and classified as natural processes (slow or rapid) and as processes or events caused by either the disposal of waste or by man. Most factors could be considered within a base case scenario with extensive parameter variation. A well scenario and extreme climate scenarios were also assessed quantitatively. The following scenarios were assessed in a qualitative way: - River/glaciation erosion - Volcanic activity - Meteorites - Earthquakes - Tectonic movements at weak zones (kakirites) - Decompression zone around repository - Canister movement in backfill - Failing of shaft sealing - Resaturation in early phase - Influence of temperature in early phase - Colloidal and microbial effects - Human influence on hydrology Volcanic activity and meteorites were deemed so improbable that the risk was considered negligible. Colloidal and microbial effects were identified as possible sources of large impact (mainly on solubility limits, sorption, and transport characteristics). However, since mechanism understanding and relevant data bases are largely missing, their impact was explicitly left open. All other scenarios were found to have consequences which were within the range of doses resulting from parameter variation in the groundwater scenarios.

Box 3B. Safety Studies based on the Judgemental Approach to Scenario Development (CEA/ANDRA and PAGIS)

Safety Study and Purpose	Scenario Analysis Approach
CEA/ANDRA: Safety analysis for licensing construction of the centre for low level waste disposal at Aube [35].	In accordance with the fundamental safety regulations for this type of disposal the following scenarios were considered: a) The normal situation. Groundwater intrusion scenarios with realistic and pessimistic assumptions regarding permeability of the cover and degradation of the barriers and the waste.
Remarks This is an example where regulations give direct guidance as to which scenarios should be treated in the safety assessment.	b) The accidental situation. Human intrusion scenarios based on the assumption that knowledge of the site has been lost. Thus a road is constructed, people live at the site, and the drinking water supply is from a well close to the site.
PAGIS: Performance assessment of geological isolation system for radioactive waste. A study coordinated by CEC covering disposal in clay, granite, salt, and sub-seabed sediments and performed from 1982 to 1987 [19].	Expert Judgement. Scenarios were classified as: a) Normal evolution scenarios involving extrapolation into the future of present and past geological trends with extensive parameter variations. b) Altered evolution scenarios involving events of a probabilistic nature that modify the conditions of the normal evolution. These scenarios are classified as short, medium, or long term. Where feasible, occurrence probabilities were estimated. Where this was not possible the consequences were assessed conditional on the event occurring.
Remarks The PAGIS report provides explicit discussion and documentation of the scenario selection procedure for every disposal option considered.	c) Disruptive scenarios describe events which have the potential to cause direct release of radionuclides to the biosphere. Examples of such events are meteorite impact, magmatic activity and tectonic displacements or glacial erosion of such amplitude that the waste repository is directly exposed. In general, due to the site selection criteria or to the nature of the disruptive events, their probability at any of the sites selected for PAGIS can be shown to be negligible, e.g., less than one chance in ten million years. For the PAGIS exercise it was decided that such rare events would not require consequence analyses.

For a number of reasons the event tree approach has been largely abandoned. First, the phenomena of importance to waste disposal assessments are slow and continuous rather than abrupt events. Second, the event tree approach is not suitable for considering the interaction and feedback between different phenomena, although such interaction and feedback are of importance for determining repository safety. Third, event trees force artificial barriers between the representation of processes, whereas the important question is how the entire system behaves. Fourth, in common with other bottom-up approaches, the number of combinations which needs to be examined becomes unmanageable unless rather drastic screening or grouping is undertaken. This is illustrated in some of the studies where the technique has been applied. The event trees are built from (even at the level of greatest detail) events that only broadly describe major release phenomena like "waste contacted by groundwater", or "fluids carry waste to the Columbia River." On the whole, attempts to apply fault and event trees to repository safety assessment have met with limited success. Since these techniques need to be complemented by judgmental methods to give concrete results their primary value has been as a means to organise the scenario selection procedure.



"E1" etc refers to an event number, "+" and "x" represent the Boolean logical operators "AND" and "OR" (i.e. "+" results in output only if input events occur simultaneously, whereas "x" results in output if at least one input event occurs).

Figure 8: Fault tree for a surface release in a study of disposal into a clay formation at the Mol Site, Belgium.

6. SYSTEMATIC METHODS TO CONSTRUCT SCENARIOS

Generating a small number of representative scenarios from a large number of events and processes in a systematic fashion is a complex task. The working group has identified two different systematic approaches to scenario formation. These approaches are termed bottom-up and top-down. This chapter also includes some observations on scenario formation.

6.1 EFFORTS IN BOTTOM-UP SCENARIO FORMATION

In bottom-up scenario formation, the screened list of features, events, and processes are combined together to form a limited number of scenarios for consequence analysis.

6.1.1 The Sandia/NRC Procedure

Sandia National Laboratories developed a structured approach to scenario selection for the United States Nuclear Regulatory Commission. Initially, it was applied for high-level waste isolation at a hypothetical bedded salt site [9,10]. More recently, it has been applied to HLW repositories in unsaturated tuff and a hypothetical basalt site [11,12,37].

The Sandia Method uses bottom-up techniques for scenario formation. This method, particularly as it was applied in earlier assessments, focused explicitly on disruptive features, events, and processes. That is, phenomena that would lead to changes in the repository and/or natural environment and initiate or modify radionuclide release and transport mechanisms. Thus the lists of phenomena under consideration are rather short. See Box 4. The phenomena are characterised as either release phenomena, or transport phenomena depending on their effect, usually on the groundwater mediated pathways.

Phenomena that remain after screening can be grouped into a single composite release or transport phenomenon if they have similar effects. Scenarios can then be constructed by taking all combinations of occurrence or non-occurrence of remaining

Box 4. Potentially disruptive features, events, and processes for a hypothetical HLW repository in bedded salt [10].

NATURAL PHENOMENA AND PROCESSES

Celestial Bodies
- Meteorites

Surficial Phenomena and Processes
- Erosion/sedimentation
- Glaciation
- Pluvial periods
- Sea level variations
- Hurricanes
- Seiches
- Tsunamis
- Regional subsistence or uplift (also applies to subsurface)
- Landslides

Subsurface Phenomena and Processes
- Earthquakes
- Volcanic activity
- Magmatic activity
- Dissolution cavities
- Interconnected fracture systems
- Faults

HUMAN INDUCED PHENOMENA AND FEATURES

Inadvertent Intrusions
- Explosions
- Drilling
- Mining
- Waste disposal (e.g. injection well)

Undetected Features
- Boreholes
- Mines

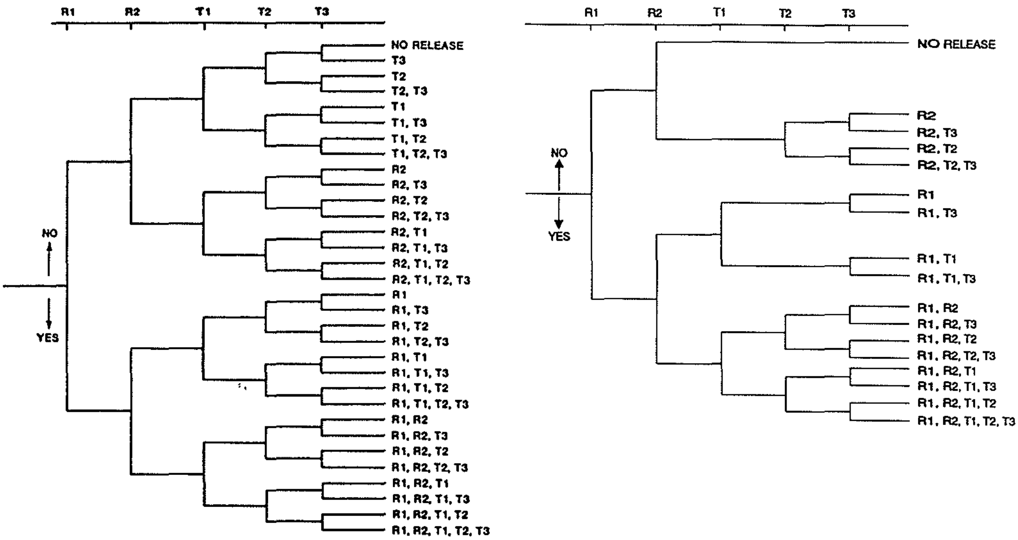
Hydrologic Stresses
- Irrigation
- Dams

WASTE AND REPOSITORY INDUCED PHENOMENA PROCESSES

Subsidence and caving
Shaft and borehole seal degradation
Thermally-induced stress or fracturing in host rock
Excavation-induced stress or fracturing in host rock

release and transport phenomena to form an event tree. See Figures 9A and 9B. However, some of these combinations are physically unreasonable or insignificant leaving a smaller number of scenarios that need to be considered in detail.

To analyse complex combinations of release and transport phenomena, a more detailed event tree procedure has been developed [37]. In this procedure, the first entry in the tree is a brief description of an event or process that might initiate a sequence of phenomena leading to release of radionuclides from the repository. Then brief descriptions of phenomena that could conceivably follow are added. Phenomena that enhance, rather than degrade, the effectiveness of the repository are not considered.



Figures 9A and 9B: Figure 9A is an event tree showing potential combinations of two releases and three transport phenomena [10]. Figure 9B is a screened event tree showing meaningful combinations of two release and three transport phenomena [37].

The performance assessments that included the development/application of the Sandia/NRC procedure were limited to groundwater mediated release and transport scenarios. The scenario in which modifying phenomena do not occur is referred to as the base case and represents a continuation of the estimated present day regime. Other scenarios were handled by calculations which show that modification to the groundwater flow regime is negligible, or as perturbations or new flow pathways superimposed on the base case. Box 5 illustrates this for the case of the hypothetical HLW repository in basalt [12]. In this case, these seven scenarios were selected as being most important and representative from an original total set of 318 scenarios [37].

Box 5. List of scenarios selected for consequence analysis for a hypothetical HLW repository in basalt and their treatment [12].

SCENARIOS	TREATMENT
1. Thermohydrological effects (heat loading) 2. Mechanohydrological effects (glaciation)	2D thermal and mechanical calculations show the phenomena have negligible effect over the time scale of interest (10,000 year)
3. Pre waste emplacement groundwater flow	Base case: 3D local and regional groundwater flow models and network (multi-dimensional network of 1D legs)
4. Pumping of groundwater 5. Change of river location	Simulated by modification of piezometric heads in the regional groundwater flow model
6. Borehole drilling 7. Formation of fault	Simulated by high hydraulic conductivity conduit or zone in the local groundwater flow model.

6.1.2 The Joint SKI/SKB Scenario Development Project

The Swedish Nuclear Power Inspectorate (SKI) and Swedish Nuclear Fuel and Waste Management Co. (SKB) have carried out a joint scenario development exercise using the Sandia method as a starting point [5,17]. Although the study has used a hypothetical repository for spent fuel based on the KBS-3 concept as its subject, an important aim of the project has been to more generally develop the scenario method. From the scenario formation point of view, an important difference between the SKI/SKB project and the earlier Sandia scenario development projects is that all features, events, and processes that might influence the long-term performance of the repository, i.e. not just disruptive phenomena, are included. The final merged list from four independent expert groups included about 150 FEPs. This did not include phenomena which influence the biosphere only; these were explicitly excluded since biosphere scenarios were to be the subject of a separate exercise.

In order to help organise the large number of FEPs remaining after screening, the Process System was introduced.

> One category of FEPs are basically major external events (e.g. climate change) whereas another category of FEPs are phenomena (e.g. fuel dissolution) that the major events or "primary causes" control. Only FEPs

representing primary causes should be combined into scenarios, whereas the more detailed phenomena could be regarded as always present (in "operation" or in standby) ... The FEPs which are determined by the external events should be brought out from the scenario development and instead be assigned to a new category, the Process System. The Process System may be defined as the organised assembly of all phenomena (FEPs) required for the description of barrier performance and radionuclide behaviour in a repository and its environment, and that can be predicted with at least some degree of determinism [17].

In this manner FEPs are sorted into those which can be represented by the performance assessment model available, and those which determine boundary conditions. Thus, in any scenario analysis, the Process System will depend on the models in mind and will vary with model capability.

One case to consider is that in which two different release and transport pathways are identified, i.e., groundwater and gas pathways. In this case a process system is required for each model and each model generates boundary conditions for the other. Organisation of the problem in this way may be perfectly acceptable but it should be explicitly recognised that scenarios are being generated with existing, or planned, model capabilities in mind.

Box 6. List of primary FEPs kept outside the Process System including isolated scenarios [17]. It should be noted that the list contains FEPs which are not mutually exclusive e.g. permafrost, change in sea-level, and glaciation are closely linked. They represent important aspects of one primary cause i.e. climate change. Such interrelationships will have to be considered in the scenario formation and selection.

2.5.1	Random canister defects-quality control
3.2.11	Backfill material deficiencies
4.2.6	Faulting
5.3	Stray materials left
5.9	Unsealed boreholes and/or shafts
5.16	Uplift and subsidence
5.17	Permafrost
5.27	Human induced actions on groundwater recharge
5.31	Change in sea level
5.42	Glaciation
7.8	Altered surface water chemistry by humans
5.2	Non-sealed repository (ISOLATED)
5.10	Accidents during operation (ISOLATED)
5.33	Waste retrieval, mining (ISOLATED)
5.38	Explosions, Sabotage (ISOLATED)
5.39	Post closure monitoring (ISOLATED)

The SKI/SKB exercise exempted sixteen primary (i.e. scenario generating) FEPs from the Process System. See Box 6. Five of these were termed isolated and inappropriate for further scenario formation consideration. They required a separate assessment. The remaining eleven FEPs might also be used to construct scenarios, but it is not possible to fully analyse the full number of combinations ($2^{11} = 2048$).

One way to consider the details of phenomena and couplings, is to divide the process system into a set of barriers, e.g. canister, near field, far field, and combinations, which could then be analysed. This yields a maximum of $3^3 = 27$ scenarios. This "top-down" approach is discussed in Section 6.2.

6.1.3 The Canadian Scenario Analysis Project

Atomic Energy of Canada Ltd. (AECL) has performed a scenario analysis for the post-closure assessment of spent fuel disposal in deep crystalline rock [16,38]. The procedure adopted is based on the Sandia method and is similar in several respects to the SKI/SKB analysis. From the point of view of scenario formation, notable features of the exercise are the use of a "central scenario" and probability estimates.

In the Canadian scenario analysis study the relevant phenomena, a list of over 1000 factors, including those affecting the performance of the biosphere were reduced to 275 general factors. Of these, 125 were identified as requiring quantitative treatment, the others being eliminated by qualitative arguments. To make the construction of scenarios from the 125 factors more tractable the concept of a "central scenario" was introduced.

> The central scenario contains as many factors as possible. As a general rule, these factors are expected to be always important, or to occur frequently or to be capable of proceeding to a significant degree over the time scale of assessment. A factor may be excluded from the central scenario for several reasons, such as: it would be important only rarely or under unusual conditions, or its presence is incompatible with the presence of another factor, or its exclusion will simplify subsequent mathematical analysis [38].

Residual factors can then be grouped in all possible combinations to form alternative scenarios, such that: "each alternative scenario contains a unique combination of one or more of the residual factors, plus factors from the central scenario" [38].

In the analysis, 117 factors were assigned to the central scenario leaving eight residual factors; these may generate $2^8 - 1 = 255$ alternative scenarios. Screening and grouping arguments were used to reduce the eight residual factors to two, thus yielding only three alternative scenarios. See Box 7. However, in some cases the reason given for screening was related to present knowledge or models. In particular, the issue of gases and gas transport was resolved by changing the waste container design (iron baskets in the waste containers were excluded) to remove the cause of the gas generation of concern. This is an example of feedback from performance assessment to system engineering.

In view of the Canadian regulatory criteria, which include a risk guideline, the AECL group assigned probabilities to scenarios. However, this was done by assigning the relatively low value of 0.01 to the alternative scenarios that included one residual factor, hence 0.0001 to the alternative scenario that included both and a probability of approximately 1 (0.9799) to the central scenario.

Box 7. Illustration of the scenario formation in the Canadian study [16,38]. Most factors were incorporated in a central scenario. Residual factors were treated as shown in this box, resulting in three alternative scenarios.

In Step 4 (Construct Scenarios) the eight residual factors, listed below, would generate $2^8-1 = 255$ combinations. Step 5 (Screening) reduces the number to give three alternative scenarios. The eight residual factors are:

Vault	Geosphere	Biosphere
1. deficient borehole or shaft seals in or near vault	4. deficient borehole seals in geosphere	8. glaciation
2. cracked or degraded buffer, permeable excavation damaged zone	5. deficient shaft seals in geosphere	
3. "other" (non-fuel)	6. gas transport	
	7. high demand for well water	

The scenarios after screening include the Central Scenario and the Alternative Scenarios. The Central Scenario considers the most probable behaviour of the whole disposal system (117 factors) and includes all probable and expected factors. The Alternative Scenarios are:

I	High Geosphere Transport	Detailed hydrogeological research code will be used to study variations in permeability of parts of the geosphere e.g., deficient seals, open boreholes, undetected fractures.
II	High Demand for Well Water	Probabilistic calculations may be performed with altered networks of geosphere pathways.
III	Alternative Scenarios I and II	

In Step 5 (Screening) these three alternative scenarios were defined using the following arguments. All scenarios involving Factors 3, 6, and 8, were deleted. Factor 3 (other non-fuel wastes) was deemed outside the scope of the assessment. Factor 6 (gas transport) was resolved by altering the concept to remove the source of gas generation. Factor 8 (glaciation) was considered unlikely over the period of the quantitative modelling assessment predictions (10^4a) and would have minor effects if it did occur. Nonetheless, bounding calculations would be included in the environmental impact statement.

Factors 1, 2, 4, and 5, were combined into Alternative Scenario I for which a detailed research code would be used to devise an altered network of geosphere and vault pathways to study the effects of deficient seals, an open borehole or an undetected fracture. A scenario involving Factor 7 (high demand for well water) will be treated as Alternative Scenario II, which will be dealt with in a manner similar to Alternative Scenario I. The factors in Alternative Scenarios I and II will be combined to define an Alternative Scenario III, which will be examined similarly.

The major reason for defining these four scenarios was to simplify the mathematical modelling, especially as regards geosphere flow networks. Given the currently available models one can proceed more efficiently this way.

6.2 TOP-DOWN SCENARIO FORMATION

As discussed in the last section, it is possible to proceed in a structured fashion from a large number of events and processes to a small number of representative scenarios. It is however, very difficult to assign "degrees of belief" to scenarios in a coherent way in the bottom-up approach. To ease this difficulty, it has been suggested that a top-down approach should be taken to scenario formation in an analogous fashion to the use of fault tree analysis for nuclear reactor safety. In this approach, consequences or environmental states are postulated and the mechanism by which these states may be reached is then considered.

An extreme version of the top-down approach would be to postulate an end point, e.g. an unacceptable consequence, and imagine ways in which this might be reached. Although this might be useful to broaden the scope of scenarios to be considered, it cannot form the basis of quantitative safety assessment since the scenario set is incomplete and there is no way to assign degrees of belief in a coherent way.

6.2.1 UK DOE and SKI/SKB Investigations

A possible approach is to consider the overall performance of the major barriers of the disposal system. This approach was investigated in early work sponsored by the UK DOE. In this analysis a target event is defined, whose outcome is that of ultimate concern. In the case of the UK DOE this is whether risk is below, or exceeds, the risk target of 10^{-6} per year [39].

The main factors that are considered to affect the outcome of the target event are the performance of the various barriers i.e. vault (repository), geosphere and biosphere, see Figure 10. It was suggested that if alternative possible states of each of the barriers

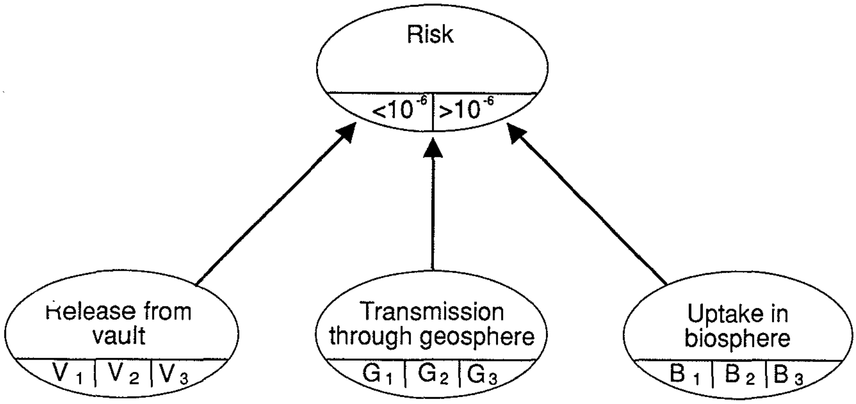


Figure 10: A "Top Down" approach to scenario construction considering three alternative states for each barrier.

can be defined and probabilities can be assigned to each state, then an estimate of the overall probability for the outcome the target event can be made by calculating conditional consequences for each of the 27 combination and combining the probability of each combination.

A similar, but less probabilistically oriented analysis was touched on during the SKI/SKB Joint Scenario Development project. In this case the "process system" was divided into three barriers, i.e. canister, near-field, and far field. It was postulated that each barrier might have different degrees of performance, i.e. ordinary, less efficient, short-circuit, and this would yield 27 possible scenarios. The link between the kept FEPs derived earlier, was made by assigning barrier states to the kept FEPs as shown in Box 8.

Box 8. Illustration of consequences on the barrier states caused by individual FEPs, from the SKI/SKB study. [17]

KEPT FEPS	BARRIER STATES Canister	Near field	Far field
Faulting	SC*	LE	SC*
Near Field deficiencies	O	LE	O
Unsealed boreholes	O	O	SC*
Uplift/subsistence	O	O	LE
Glaciation	SC*	LE	SC*
Human actions on groundwater flow and composition	O	O	LE

Key to barrier states: O = ordinary
SC = Short circuit
LE = less efficient
* = for part of repository only

6.2.2 UK Nirex Trial Scenario Development

Top down approaches have been more thoroughly investigated in research sponsored by UK Nirex in preparation for the development of a safety case for deep underground disposal of LLW and ILW in the UK [28].

The method developed for the formation of scenarios from the phenomenon list depends on dividing the repository natural environment and radiological system into component parts, termed "scenario elements" (factors). A comprehensive set of alternative states which each scenario element may adopt is then postulated. The stages of this top-down approach are as follows:

1. Define potential scenario elements.

2. Construct an influence diagram showing dependencies between scenario elements.

3. Define a comprehensive set of states for each scenario element.

4. Form a scenario element state tree in which each combination of states defines a potential scenario.

5. Screen the combinations of scenario element states by rejecting non-physical and unimportant combinations to arrive at a set of scenarios for consequence analysis.

6. Assign "degrees of belief" to each scenario element state taking account of states of other elements via the influence diagram and hence derive scenario probabilities.

The first three stages may be iterated on in order to arrive a most logical and appropriate definition of scenario elements and states. The list of phenomena derived, as discussed in Chapter 4, acts as a check list for the procedure.

Scenario elements may be defined based on: cause (e.g. natural phenomena, human activities, repository effects) which may be convenient for the construction of an influence diagram; field of effect (e.g. near field, far field, biosphere, or release, transport, exposure) which may be convenient as a starting point for modelling; or combinations of these. The main advantages of the top-down approach are that the scenario element states can be defined to be intrinsically comprehensive, and thus "degrees of belief" can be coherently assigned using expert judgement.

From UK Nirex's point of view the top-down approach is helpful since it allows a more justifiable assignment of probabilities, and hence enables calculations of risk for comparison with the UK risk target. From a more general standpoint the method is attractive since the scenario set, formed by all allowable combinations, is demonstrably complete, if the alternative states are complete. The difficulty is that the link between the extensive phenomenon lists and the alternative states must be made in order to demonstrate this. In order to improve the link between phenomenon lists and scenarios a much more detailed analysis was performed in which a large number of "scenario elements" and alternative "element states" were defined.

A "scenario element" can be any important process or group of features and processes that affects the performance of the repository, geosphere or biosphere. These were identified by examination of the list of phenomena remaining after screening. For each scenario element, a set of states was defined which are mutually exclusive and comprehensive. This latter is important if probabilities of scenarios are to be coherently assigned.

Over 40 "scenario elements" were derived each with 2, 3, or 4 alternative "states". Influence diagrams were constructed to plot the influence between elements; this helped to refine and extend the list and definitions of scenario elements and states. Part of the influence diagram constructed is shown in Figure 11.

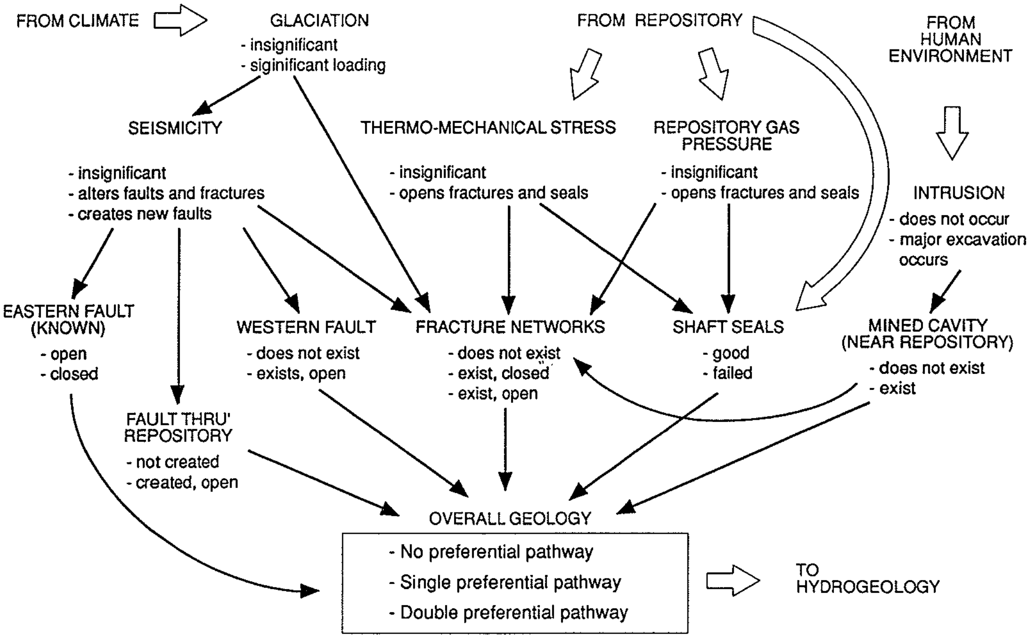


Figure 11: Part of an influence diagram for scenario elements and states from the Nirex Trial Scenario Development

The influences can be thought of as probability conditioning. That is if the state adopted by one element affects the probability that is assigned to states of another element. It was recognised that the system can now be simplified by screening the influences. They can be deleted if the feature or process is judged, or calculated, to have an insignificant effect in determining the state of another element; or the probability conditioning can be replaced by determination if the adoption of one particular state by an element would lead to, or is strongly associated with, a particular state of another element. Thus many elements can be reduced to "determined" or "fixed" elements leaving a smaller number of elements to generate scenarios.

In the analysis made for Nirex, the system was reduced to five "scenario generating" elements, with some residual influence, by the process of influence screening, see Figure 12. Probabilities P_I, were assigned subjectively to each state of each scenario generating elements such that the sum of the probabilities equals one. This was done taking account of the residual influences; that is, there is a preferred order in which probability assignment of element states is addressed and probabilities assigned are conditional on the state of other elements. This was kept track of by a probability assignment tree similar to the event trees used by Sandia. The exercise was carried out independently by six experts and there was a fair degree of agreement between assignments.

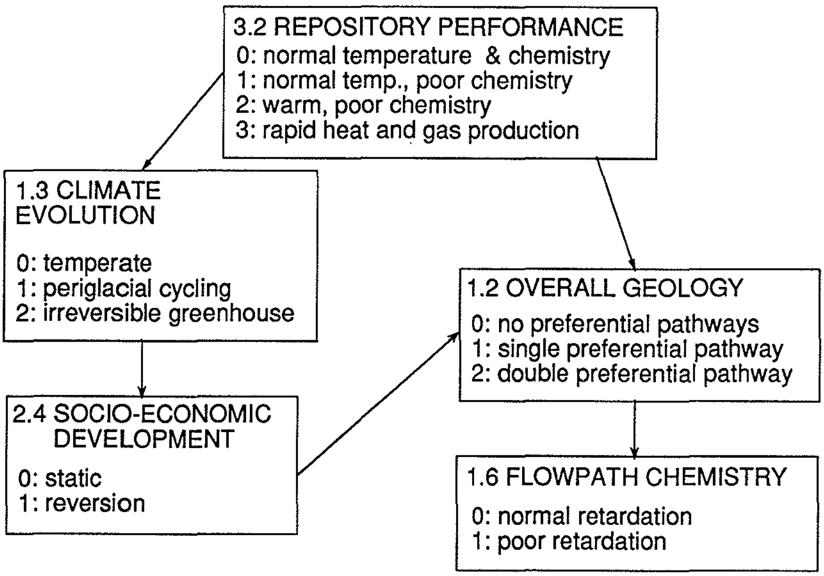


Figure 12: Potential scenario element and states and direction of residual influences from a trial scenario development sponsored by UK Nirex.

6.3 SOME OBSERVATIONS ABOUT SCENARIO FORMATION

Approaches to scenario formation have to rely to a significant extent upon the judgement of those performing the study, because in most cases the list of factors are normally too extensive to allow all possible combinations to be equally considered. Some general observations are discussed below.

6.3.1 Scenario formation is linked to modelling

Scenario formation can be seen as a link between the list of individual factors and phenomena that need to be considered in the safety study and the eventual modelling and consequence calculations. Thus, it is obvious that scenario formation is influenced by the types of models and calculation tools that are available. The reverse is also true i.e. findings during scenario development may identify needs for development of additional quantitative models. One example is the identification, for some disposal concepts, of gas generation as an important factor to be considered and where quantitative modelling is needed.

6.3.2 The use of a central or base case scenario

Most studies (e.g. the Swedish and Canadian examples discussed above and the Swiss Gewahr Study, see Box 9) indicate clearly the usefulness of defining a central or base case scenario. It serves as a backbone to the scenario formation (and the modelling) against which the potential importance of additional FEPs can be judged.

6.3.3 Human intrusion - A special case

A special category of scenarios are those related to future human activities that may disrupt the barrier system of a repository. In fact, in many cases, the repository concept and site provide such good conditions for safety that potential human actions become the dominant mechanism leading to risk from the disposed waste. This may be particularly true for shallow disposal of radioactive waste, but also in the assessment of deep repositories, intrusive actions by man at or close to the site will have to be considered.

Any attempt to predict effects of future human activities on a radioactive waste repository will be subjective in nature because man himself is involved. Thus, the problem of human intrusion should be approached with moderation and balance, clearly recognising the limitations in what can be done. One cannot scientifically predict how man and society will develop and what uses, for instance, there will be of the Earth's subsurface environment thousands of years from now. On the other hand, based on past

Box 9. In the Swiss Gewahr Study a groundwater base case scenario was identified and by parameter variations most scenario mechanisms (FEPs) could be considered using the existing base case models [14].

EFFECTS OF SCENARIO MECHANISMS ON THE BASE SCENARIO MODEL CHAIN

SCENARIO MECHANISM	MODEL CHAIN									
	RH	LH	NFH	C	NFC	SL	L	RTNF	RTFF	BT
Slow Natural Processes										
Climatic change										●
without glaciation	●									
with glaciation	●									
Erosion										
fluvial	●	●								
glacial	●									
Sedimentation	●	●								
Tectonic crustal movement	●	●								●
Volcanism	●									
Diagenesis	●	●	●						●	
Metamorphosis	●	●			●				●	
Weathering, mineralisation	●	●			●				●	
Rapid Natural Events										
Earthquakes			●							
Meteor impact	●	●								
Movements at faults	●	●								
New formation of faults	●	●								
Repository and Waste Induced P/E										
Radiation damage							●			
Radiolysis					●					
Canister movement in backfill			●							
Decompressed zones			●							
Mechanical canister damage			●	●						
Differing thermal expansion of host rock zones		●	●							
Thermal convection			○							
Gas production			○	●						
Thermally induced chemical changes				●	●	●	●			
Resaturation			○							
Chemical changes through corrosion					●	●				
Colloid formation					●			●	●	
Microbiological processes				●	●	●				●
Failure of shaft sealing			●							
Processes and events caused by man										
Direct changes in hydrology	●	●								●
Injection of liquid wastes		●	●							
Drilling into sediments		●								●
Geothermal energy production in crystalline rock		●								●

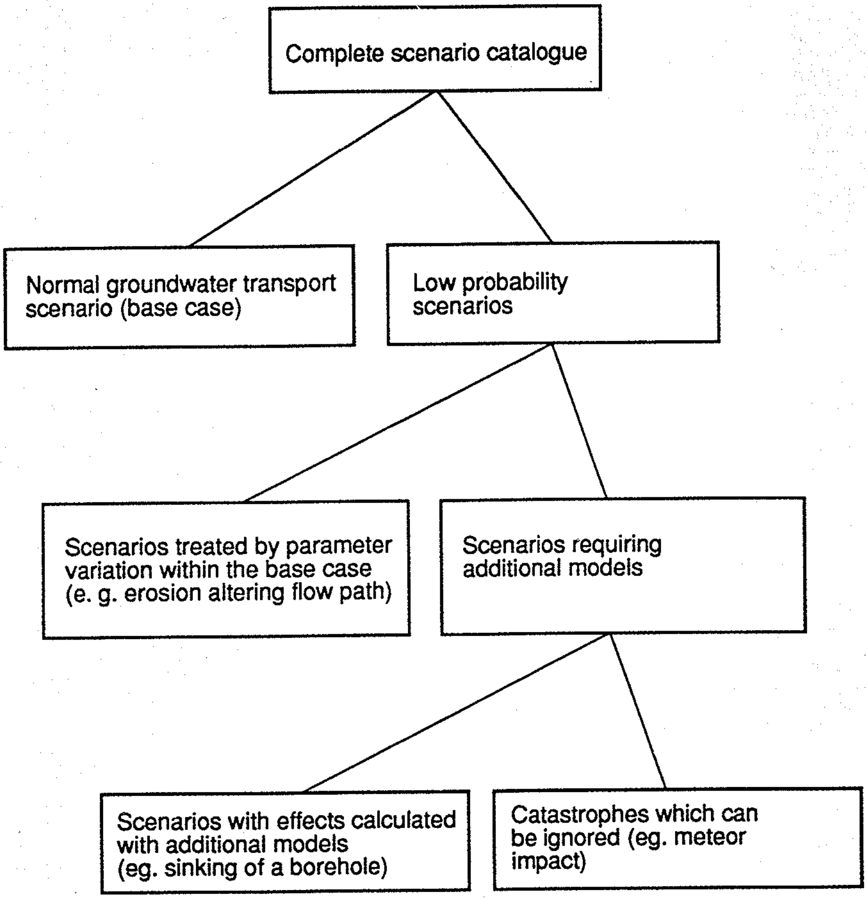
● Direct Parameter Change
○ Change in Conceptual Model

RH Regional Hydrology
LH Local Hydrology

NFH Near Field Hydrology
NFC Near Field Chemistry
L Leaching Waste Matrix
SL Chemical Speciation
C Cannister Corrosion

RTNF Radionuclide Transport Near-field
RTFF Radionuclide Transport Far-field
BT Biosphere Transport

Box 9 (Cont'd).


Complete scenario catalogue
Normal groundwater transport scenario (base case)
Low probability scenarios
Scenarios treated by parameter variation within the base case (e. g. erosion altering flow path)
Scenarios requiring additional models
Scenarios with effects calculated with additional models (eg. sinking of a borehole)
Catastrophes which can be ignored (eg. meteor impact)

history and present day conditions, it is possible to discuss in a meaningful way how man might interfere in the future with a repository. This will illustrate potential risks from human intrusion and it will help to develop waste disposal practices that can be considered sufficiently invulnerable to human intrusion. Assessments of human intrusion are therefore now seen as a necessary part of overall safety studies. See Box 10. The study may provide important information that will help in decision making regarding appropriate concepts and designs of waste repositories, and their siting, as well as any possible restrictions on the types of wastes that should be accepted for a particular type of repository.

A detailed discussion of issues related to human intrusion was outside the scope of the Scenarios Working Group. However, as proposed by this group, the NEA organised a workshop on human intrusion in 1989 [40]. As a follow-up action a special working group on "the Assessment of Future Human Actions at Radioactive Waste Disposal Sites" was constituted in early 1991. This group will attempt to develop some international consensus regarding reasonable approaches to assessment of potential future human intrusions.

Box 10. Some basic questions regarding human intrusion scenarios [41].

There is a set of basic questions about man and society in the future that needs to be discussed when making assessments of human intrusion risks.

- o How efficiently and for how long can institutional control be maintained?
- o What will be the ability to keep and understand information about the repository and the waste?
- o How do we deal with an intrusion deliberately decided upon by a future society? Or by future individuals? i.e., for recovery of resources, negligence ore even sabotage?
- o If we assume that the intruder is unaware of the waste, what do we assume about his abilities to understand and to make remedial actions once he has intruded into the repository and detected the waste?
- o 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?
- o 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?

6.3.4 Estimation of Probabilities

The calculated long-term consequences of a repository should be judged in the light of their probabilities of occurrence and therefore the probabilities associated with different scenarios must be considered. The importance of defining probabilities in a clear way has to be stressed. A clear distinction must also be made between probabilities of events/processes, probabilities of scenarios and probabilities of health effects within a certain scenario. There are several possible approaches to estimation of probabilities ranging from strict axiomatic calculations through frequentist and modelling approaches to subjective judgement estimates.

For example, the probability of occurrence of a meteorite impact at a repository site has been estimated based on data from observations of past meteoritic impacts (frequentist approach). 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 practices in the past and at present. 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 safety assessment and ensure the most appropriate use of available data and evidence.

7. ENVIRONMENTAL SYSTEM SIMULATION

Efforts are currently underway in a number of national environmental programmes to develop a basis and capacity to model environmental effects (e.g., glaciation) due to climate change [42]. The application of environmental simulation models to date has, for the most part, been limited to climate driven processes and not included phenomena caused by the operation of a repository or those due to human intrusion. However, the technique appears to have wider applicability. The system simulation approach which is now being developed in some of the assessment programmes combines environmental simulation modelling with radionuclide release and transport modelling [43].

7.1 EARLY ENVIRONMENTAL SIMULATION

The first attempt to use environmental simulation modelling to assess nuclear waste disposal safety was made in the early 1980s by Pacific Northwest Laboratories (PNL). The Geological Simulation Model (GSM) was specifically tailored to the Columbia Plateau region which contains the U.S. Department of Energy's Hanford Site [29]. See Figure 13. Using Monte Carlo sampling of probability distribution functions (pdfs) as input parameters, GSM models both continuous natural processes and sudden events. Since the pdfs are largely derived from expert judgement, the output result needs to be treated with considerable caution.

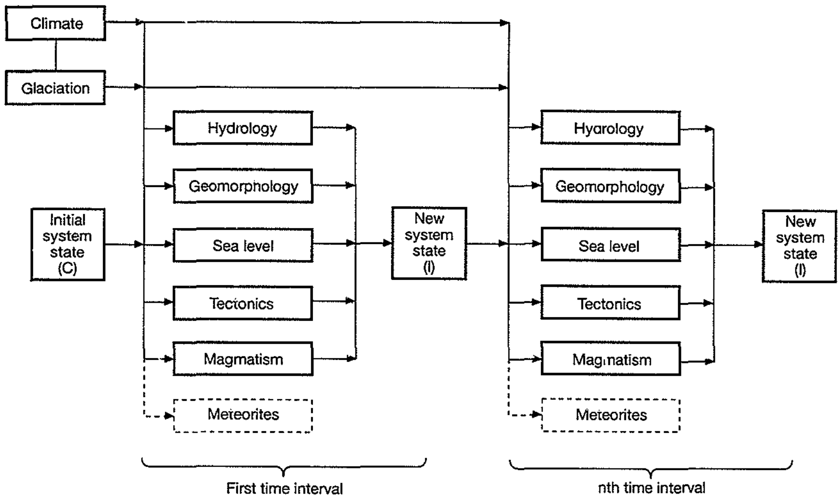


Figure 13: Schematic diagram of the operation of the simulation model (GSM) [44].

The Far Field State Model (FFSM), a non site specific, stochastic environmental simulation model was also developed in the United States and contains a far wider range of events and processes, namely: undetected features, climate, glaciation, folding, diapirism, magmatic events, faulting, regional deformation, geomorphic processes, dissolution fronts, breccia pipes, solution mining, and drilling [30]. Neither GSM or FFSM have been applied in assessment projects in the United States.

In the last few years several environmental simulation modelling efforts have been made in Europe. In France, the Bureau of Geological and Mineral Research, with the help of the CEC, developed the CASTOR model [45,46]. CASTOR is a deterministic model which uses the combined effects of climatic and tectonic factors in modelling the evolution of the geohydrological characteristics of a site. To verify and validate the model from a purely methodological standpoint, CASTOR was applied to a sector of the Paris basin. See Figure 14. The evolution of the region over the last 100,000 years of the quartenary was reconstituted with the help of geological observation. Then the evolution was simulated with the CASTOR model and the results (erosion, changes in sea level, etc.) were compared. While effects by erosion, sedimentation, and changes in sea level could be reasonably well matched in many instances, it was impossible to link the local tectonics like vertical block movements, etc. with the global tectonic model incorporated in CASTOR. This may be a general difficulty with this type of modelling.

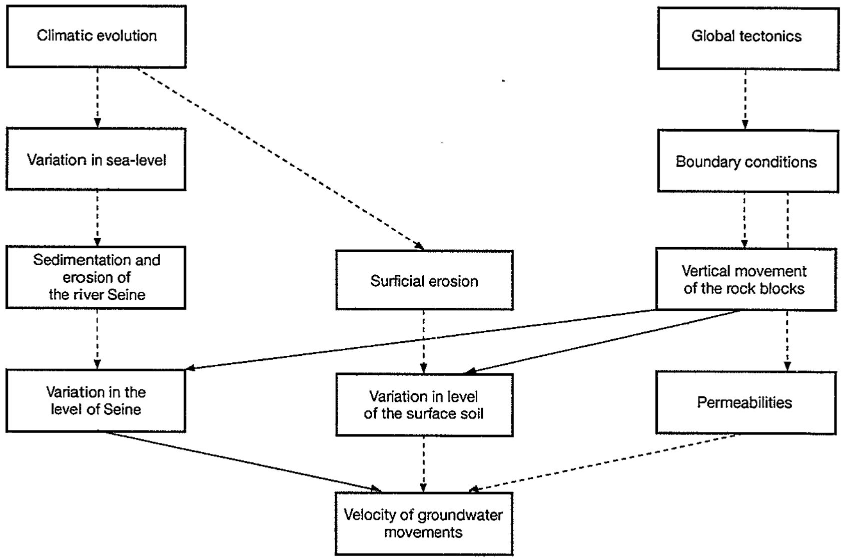


Figure 14: This figures illustrates the phenomena and interrelations included in the application of CASTOR to the Paris basin. The dotted lines indicate links that could not be modelled in this exercise because of insufficient information.

7.2 THE UK DOE SYSTEM SIMULATION APPROACH

An ambitious programme for developing environmental simulation techniques and the system simulation modelling approach has been funded and coordinated by the U.K. Department of the Environment (DOE) since 1982 [31,32]. The primary purpose of the programme has been to develop a capability to asses the radiological risk of underground waste disposal.

The UK DOE work is motivated by the need for a systems approach to the complex problem of assessing risk in situations where there are large numbers of interrelated and uncertain phenomena. It is considered that the act of formulating an overall system simulation model forces the assumptions to be examined and documented clearly. It is also argued that system simulation modelling provides a rigorous way of dealing with interactions between phenomena, and of creating coherent time sequences. Since the model, like the real system, is complex, the problems of understanding and presenting the results are very challenging. A problem with the system modelling approach, and the reason that the work was discontinued in the United States, is the difficulty in obtaining reliable pdfs for the large number of input parameters.

The first model developed under this program was the TIME2 code used to assess disposal in near surface repositories. TIME2 is a Monte Carlo simulation model of climate driven processes that are expected to cause environmental change in the United Kingdom until the next glacial maximum. TIME2 has been used to model environmental change at a potential repository site in Eastern England [47] and as a part of the U.K. DOE assessment of the low level waste site at Drigg Cumbria.

In both these cases, the environmental simulation results have been used to guide radiological consequence analysis. In the first application, results were used to construct groundwater and biosphere scenarios for three climate states (temperate, savannah and tundra) which were then individually analysed. For the Drigg site, the results have been used to construct a single, representative future prognosis. By including changes in environmental parameters the radiological impacts can be modelled in a realistic sequence. This latter approach is made possible by the use of the VANDAL code [43]. VANDAL includes a network representation of groundwater flow which responds to time dependent changes in boundary conditions and material properties.

The aim of current UK DOE work is to directly couple a newly developed Monte Carlo simulation model of environmental change over a million years (TIME4) with a new version of VANDAL aimed at the assessment of deep underground disposal. Thus, the environmental model will effectively generate a very large number of realisations for a single scenario. TIME4 generates consistent probabilities for these scenario realisations from the input pdfs and allows checks to be made concerning statistical convergence of the results. In addition, since the length of time required to develop an effective environmental simulation and radiological consequence model is fairly long, it is likely that for a given assessment, phenomena will be identified that have not been represented in the available system model. Thus additional calculations will be required and these must be sensibly related to the calculations performed by the system model. A conceptual view of a climate driven environmental system including the roles of TIME4 and VANDAL, is shown in Figure 15.

In principle, the aim is to use the best current understanding of environmental processes to build an integrated model of environmental processes and radionuclide release, transport and exposure pathways. Figure 16 shows processes and events which, it is proposed, could be modelled by TIME4 (with some enhancements) and their influence [48,49]. The motivation for adopting this course is twofold.

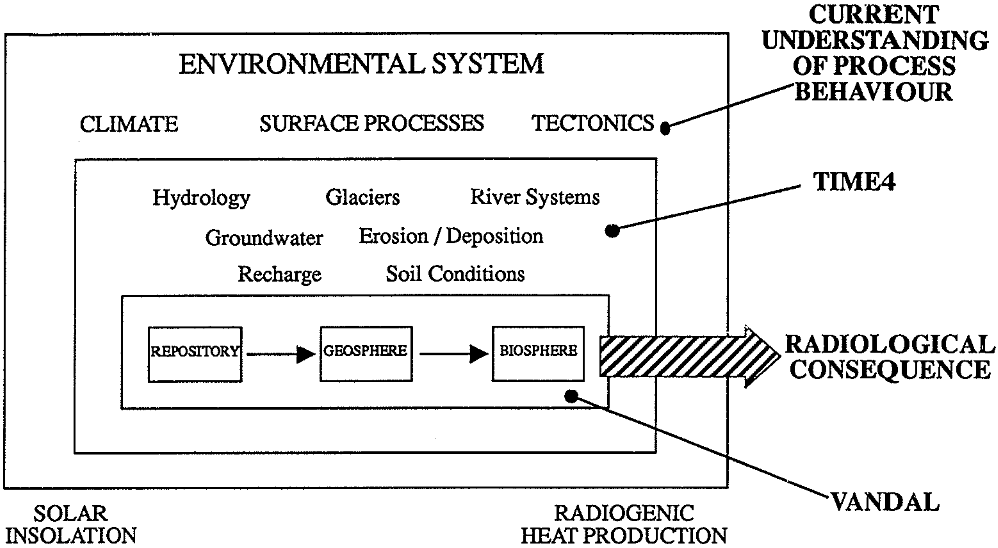


Figure 15: Radiological assessment modelling within the Earth's environmental system using TIME4 and VANDAL [42].

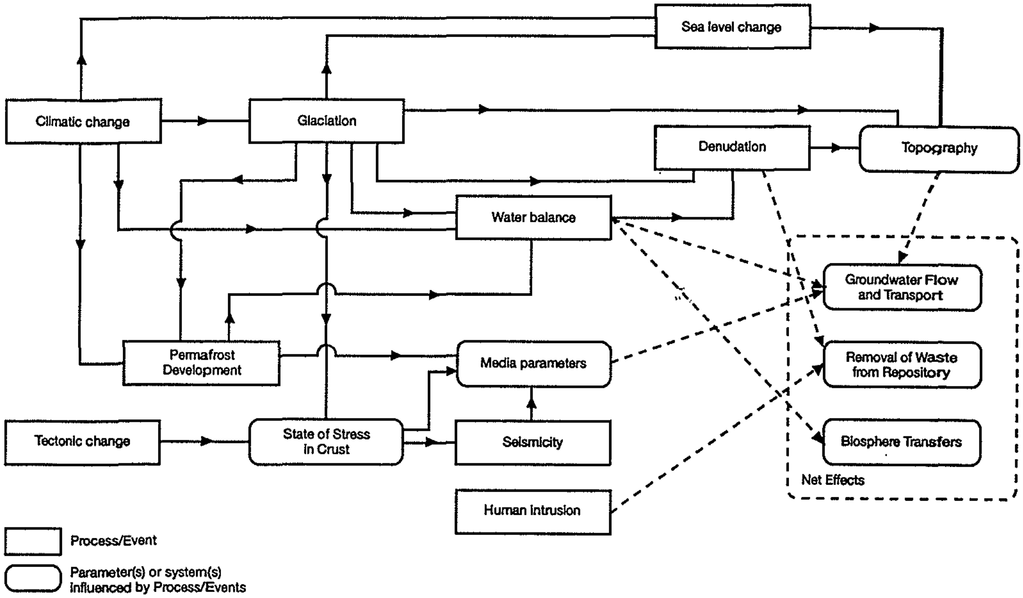


Figure 16: A conceptual model of the environment system indicating net effects on radiological transport parameters [48].

- First, the UK has adopted a risk target. In order to demonstrate compliance with the target it is necessary to investigate the full range of possible futures for the environmental system and to assign probabilities coherently to the relevant parameters so that a statistically meaningful estimate of consequence (pdf of dose) and hence of overall risk can be obtained.

- Second, the developing disciplines of quantitative climatology and geomorphology do provide a scientific basis for the estimation of the variation with time of significant environmental parameters.

Figures 17 and 18 illustrate results from the recently completed trial of the time-dependent methodology based on an assessment of a hypothetical deep underground repository for radioactive wastes at the Harwell site in the UK (Dry Run 3) [33].

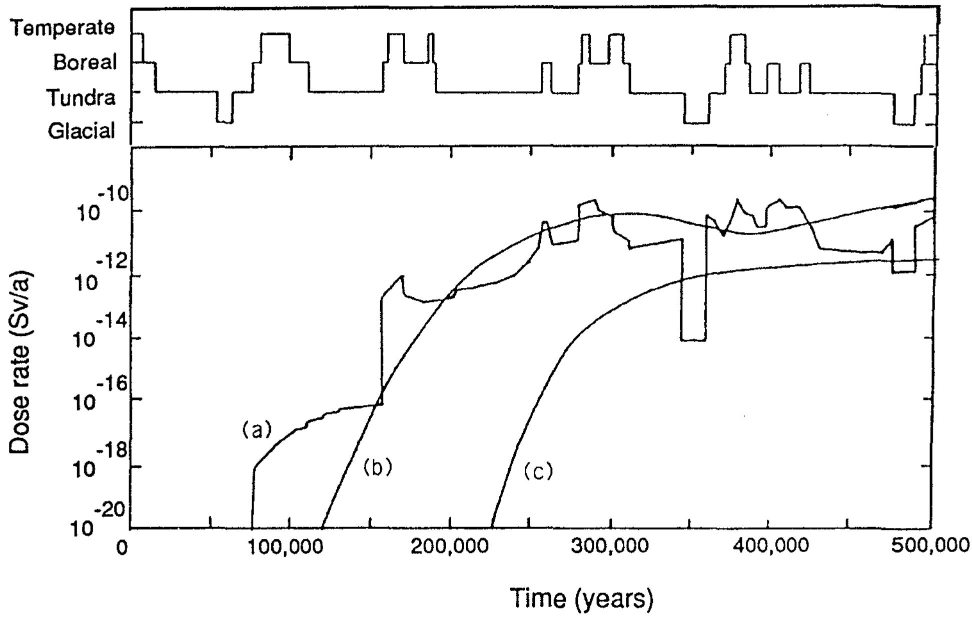


Figure 17: Comparison of individual doses for (a) the historic climate sequence (b) constant conditions present-day (c) constant tundra climate [32].

Figure 17 compares deterministic calculations of maximum individual doses from a single radionuclide for:

(a) a realistic sequence of environmental change in the UK based on the geological record;

(b) constant temperate conditions based on present day conditions; and

(c) constant tundrà conditions which may be expected to pertain during much of the next 500,000 years in the UK.

The climate sequence on which simulation (a) is based is also shown. Figure 18 compares estimates of mean risk and 95% upper confidence bounds on risk from:

(a) a fully time-dependent Monte Carlo simulation based on 500 environmental simulations; and

(b) an equivalent simulations for constant temperate conditions employing the same pdfs of non-time dependent parameters, e.g., sorption coefficients (K_d).

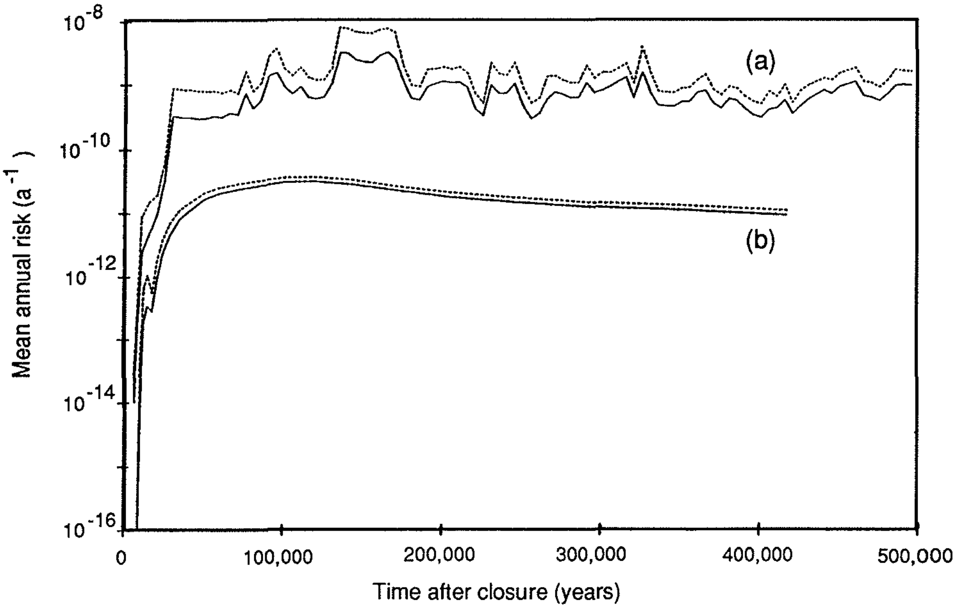


Figure 18: Comparison of estimates of mean annual risks and 95% upper confidence bounds from Monte Carlo simulations based on (a) fully time-dependent TIME4-VANDAL simulation (b) an equivalent VANDAL simulation for constant present-day conditions [33].

7.3 A SUMMARY OF SIMULATION APPROACHES

In summary, several models have been developed to simulate the long-term evolution of the environment [29,30,31,32]. To date, this has concentrated mainly on the effects of climate driven change, and geological processes, although models for the simulation of human intrusive activities have also been proposed [50,51]. The main characteristics and use of the environmental simulation codes reported are summarised in Box 11.

It must be recognised that the value of such models is critically dependent on the attention paid to initial selection of phenomena to be included in the models. In some cases this process has been explicitly documented, e.g. [48], and can be similar to the phenomena elicitation and screening processes included in scenario development.

Box 11. Characteristics of environmental simulation models for radioactive waste disposal sites reported in the literature.

Name	Scope	Applications
GSM Geologic Simulation Method	Stochastic site specific model accounting for effects of climate change and glaciation on hydrogeology, geomorphology, sea level changes, plate tectonics, and magmatism	Trial simulation for Columbia Plateau region, USA.
FFSM Far Field State Model	Stochastic non-site specific "tool-kit" based on, but with wider range of processes, than GSM.	None reported.
CASTOR	Deterministic model accounting for effects of climate change and tectonics on erosion, sedimentation, sea-level changes and groundwater travel time.	Validation for the Paris Basin, France.
TIME2	Stochastic non-site specific model accounting for effects of climate change (up to a 1st glacial maximum) on topography, erosion, seal level, recharge, and surface hydrogeology at a shallow site.	Trial simulation for the Elstow site, UK.
TIME4	Stochastic non-site specific model accounting for climate change (over multiple glacial episodes) on topography, erosion, sea level, recharge surface hydrogeology and permafrost development at a deep disposal site.	Trial simulation for the Harwell site, UK.

Originally these models were intended, and have been used, to explore the environmental evolution of a defined location in preparation for calculating radiological impact. Used in this mode they may be regarded as tools to assist in the scenario development and may be of special value in quantifying environmental parameters in otherwise qualitatively described scenarios.

Only the UK DOE has attempted to couple the output from an environmental simulation model directly to the more traditional radiological assessment models covering the groundwater-mediated release and transport.

The Purposes of Environmental Simulation

The scientific basis and tools for environmental simulation are rapidly being improved. In the context of safety assessments of radioactive waste disposal, environmental simulation could be used in several ways, for example:

- to give insight and results about possible long term evolution or the environment that can be used to guide scenario formation;

- to model certain scenarios, e.g. a glaciation scenario.

- to be fully integrated in a complete simulation of disposal system performance for a probabilistic risk assessment.

Work is going on along these lines and only after further experience will it be possible to clearly judge the full potential and justification for using environmental simulation techniques. Under all circumstances such judgements will depend upon particular regulatory requirements and resources in each country.

8. FINAL REMARKS AND CONCLUSIONS

This chapter brings together the major observations and conclusions of the working group about scenario development for post closure performance assessment of radioactive waste disposal.

1. Scenarios are broad descriptions of alternative futures.

Scenario development is the first step in performance assessment. It is followed by modelling and consequence calculations. Thus in the view of the working group, scenario development does not encompass the definition of models or the provision of data. Scenario development, according to this interpretation, will only result in a specification of the features, events, and processes that need to be considered further and a broad brush description of their characteristics and sequencing. After this there still remains the task to move to definition of specific calculations where the models and data are defined.

2. Scenario development is part of the iterative performance assessment procedure.

Scenario development is not done in a vacuum. It is influenced by and uses information from previous modelling and consequence calculations. According to the working group, however, it is important that it be distinguished as a separate step in the assessment procedure because that will force the assessor from time to time to come back to the questions about comprehensiveness and overall relevance of his safety study. (Has anything been overlooked initially?)

3. Identification and screening of potentially important factors (FEPs) is needed for all scenario development.

There is a consensus about the need and approach to be taken to developing a list of phenomena that need to be considered in safety assessments. The approach should involve people with a wide variety of expertise and systematically compile and define a comprehensive list of potentially important features, events, and processes. Considerations and decisions made in drawing up and screening the list should be adequately documented.

4. Scenario formation can be made in several ways and human judgement is an important element of scenario formation.

For comprehensive safety assessments the list of potentially important factors (FEPs) is normally too large to allow any detailed consideration of all possible combinations of them. There are, however, scenario formation procedures that allow the judgement and reasoning power of experts and generalists to be integrated with quantitative considerations so that they result in a manageable number of representative scenarios through a well-defined screening procedure.

5. Simulation and scenarios approach are complementary rather than separate alternatives.

The working group has had extensive discussions about the differences and similarities of the scenarios and simulation approaches. The group considers that these approaches should be seen as parts of the suite of tools available to be used in concert to set up and perform safety assessments.

In an actual case the purpose, scope, regulatory requirements and resources associated with the study will determine the most appropriate approach. It is clear that already now and even more so in the future, scenario development will benefit from the rapid development of environmental simulation techniques. Similarly, integrated simulation techniques, need the results of systematic and well documented phenomena elicitation to be able to construct a computer model of the evolving environment.

In both approaches the FEPs are evaluated and screened. In the system simulation approach the temporal behaviour and consequences of the FEPs which are considered to be relevant are modeled in one single model. In the scenarios approach the FEPs are combined into scenarios which are represented either by altered boundary conditions of a model or by different models.

6. Probability estimations of scenarios (alternative futures) have to be based to a large extent on expert judgement and are associated with significant uncertainties.

Estimation of the probability of events and processes, and of scenarios or estimation of parameter probability distribution functions for simulation models is a particularly difficult aspect of scenario development. The need for such estimates will depend upon the type of assessment done and regulatory criteria. It will involve use of existing data in areas like resource exploration, climatology, tectonics, seismicity, and volcanology coupled with expert judgements. It is important that such estimates be carefully documented so that the exercise is traceable and thereby open to scrutiny.

REFERENCES

[1] NEA SCENARIO CATALOGUE. A compilation of questionnaire responses on scenarios for performance assessments of radioactive waste disposal. OECD/NEA, Paris, 1988

[2] Systematic Approaches to Scenario Development. A Preliminary Report of the NEA Working Group on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal [PAAG/DOC(88)2].

[3] Thompson, B.G.J. A method of overcoming the limitations of conventional scenario-based risk assessments by using Monte Carlo simulation of possible future environmental changes. Technical Report TR-DoE-12 [also PAAG/DOC(88)11], Her Majesty's Inspectorate of Pollution, Department of the Environment.

[4] Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites. Proceedings of an NEA Workshop, OECD/NEA, Paris 1989.

[5] Safety Assessment of Radioactive Waste Management. Proceedings of the Paris Symposium 1989, OECD/NEA, Paris, 1990.

[6] Andersson, J. and Eng T. The Joint SKI/SKB Scenario Development Project. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[7] Escalier des Orres, P., Devillers, C., Cernes, A. and Izabel, C. Détermination des scénarios à prendre en compte dans l'appréciation de la sûreté d'un site pour le stockage des déchets radioactifs en formation géologique profonde. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[8] Disposal of Radioactive Waste: Review of Safety Assessment Methodologies. A Report of the Performance Assessment Advisory Group of the Radioactive Waste Management Committee, OECD/NEA, Paris, 1991.

[9] Cranwell, R.M. et al. Risk Methodology for Geologic Disposal or Radioactive Waste: Scenario Selection Procedure. NUREG/CR-1667, SAND80-1429, December 1982, revised April 1990.

[10] Cranwell, R.M. et al. Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report. NUREG/CR-2452, SAND81-2573, August 1987, first published 1982.

[11] Guzowski, R.V. et al. Potential Scenarios for Use in Performance Assessment of High-Level Radioactive Waste Repositories in Unsaturated Tuff. NUREG/CR-4770, SAND86-7170, in preparation.

[12] Bonano, E.J. et al. Demonstration of a Performance Assessment Methodology for High-Level Radioactive Waste Disposal in Basalt Formations. NUREG/CR-4759, SAND86-2325, June 1989.

[13] Bonano, E.J. et al. The Use of Expert Judgements in Performance Assessment of High-Level Waste Repositories. In Safety Assessment of Radioactive Waste Repositories. Proceedings of the Paris Symposium, OECD, Paris, 1990.

[14] NAGRA: Projekt Gewähr 1985 - Feasibility Study; NAGRA Project Gewähr Report Series NGB 85-01 - NGB 85-09, NAGRA, Baden, Switzerland, 1985.

[15] Environmental Protection Agency. Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule. 40 CFR Part 191, Federal Register 50 (182), Washington D.C., 1985.

[16] Stephens, M.E. and Goodwin, B.W. Scenario Analysis for the Post Closure Assessment of the Canadian Concept for Nuclear Waste Disposal. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[17] Andersson, J. et al. The Joint SKI/SKB Scenario Development Project. SKI Report TR 89:14, October 1989.

[18] Report by the National Academy of Sciences Committee on Waste Disposal, United States, 1955.

[19] CEC: Performance Assessment of Geological Isolation Systems for Radioactive Waste - Summary. CEC Nuclear and Science Report Series PAGIS, EUR 11775EN, 1988.

[20] Wuschke, D.M., Gillespie, P.A., Metha, K.K., Heinrich, W.F., Leneveu, D.M., Sherman, G.R., Guvanasen, V.M., Donahue, D.C., Goodwin, B.W., Andres, T.H., Lyon, R.B.: Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal, AECL-8373-4, 1985.

[21] National Research Council: A Study of the Isolation System for Geologic Disposal of Radioactive Wastes; National Academy Press, Washington D.C., 1983.

[22] SKBF/KBS: Final Storage of Spent Nuclear Fuel - KBS-3; Stockholm, 1983.

[23] Bingham, F.W. and Barr, G.E. Scenarios for Long-Term Release of Radionuclides from a Nuclear Waste Repository in the Los Medanos Region of New Mexico. Sandia National Laboratories Report SAND78-1730, 1979.

[24] Hunter, R.L. Preliminary Scenarios for the Release of Radioactive Waste from a Hypothetical Repository in Basalt of the Columbia Plateau. U.S. Nuclear Regulatory Commission Report NUREG/CR-3353, 1983.

[25] Hunter, R.L., Barr, G.E. and Bingham, F.W. Scenarios for Consequence Assessments of Radioactive Waste Repositories at Yucca Mountain, Nevada Test Site. Sandia National Laboratory Report SAND82-1277, 1983.

[26] Roberds, W.J., Plum, R.J. and Visca, P.J. Proposed Methodology for Completion of Scenario Analysis for the Basalt Waste Isolation Project, Rockwell Hanford Operations Report RHO-BW-CR-147P, 1984.

[27] D'Alessandro, M., Bonne, A. Radioactive Waste Disposal into a Plastic Clay Formation. CEC Report EUR7111 (also by Harwood Academic Publishers, 1981).

[28] Billington, D.E. et al. Radiological Assessment of Deep Geological Disposal: Work for UK Nirex Ltd. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[29] INTERA Environmental Consultants Inc., GSM: Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau: Large Computer Version of Nuclear Waste Isolation Report ONWI-447, 1983.

[30] INTERA Environmental Consultants Inc., FFSM Far-Field State Model, Office of Nuclear Waste Isolation Report ONWI-436, 1983.

[31] Ringrose, P.S. et al. Probabilistic Simulation of the Long-Term Evolution of Radioactive Waste Disposal Sites. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[32] Thompson, B.G.J. The Development of Procedures for the Assessment of Underground Disposal of Radioactive Wastes: Research Funded by the Department of the Environment, 1982-87. Rad. Waste Man. and the Nucl. Fuel Cycle, Vol. 9, pp. 215-256, 1987.

[33] Summerling, T.J. Dry Run 3: A trial of methodology for the probabilistic risk assessment of underground disposal of radioactive waste that accounts for long-term environmental change: Overview. UK DoE Report TR-DR3-10 (to be published) 1991.

[34] International Atomic Energy Agency. Safety Assessment for the Underground Disposal of Radioactive Wastes. Safety Series No. 56, IAEA, Vienna, 1981.

[35] Izabel, C. and Leveel, S. Analyse de sûreté du centre de stockage de l'Aube. In the Proceedings of NEA/IAEA/CEC Symposium, Paris 1989.

[36] Logan, S.E. and Berbano, M.C. "Geologic Modelling in Risk Assessment for Radioactive Waste Management" in Risk Analysis and Geologic Modelling in Relation to the Disposal of Radioactive Wastes into Geological Formations. Proceedings of an OECD/NEA and CEC Workshop in Ispra, 23-27 Mai 1977, pp. 77-1158.

[37] Hunter, R.L. Preliminary Scenarios for the Release of Radioactive Waste from a Hypothetical Repository in Basalt of the Columbia Plateau. NUREG/CR-3353, SAND83-1352, 1983.

[38] Goodwin, B.W. et al. Scenario Analysis for the Post Closure Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal. AECL Draft Report, 1989.

[39] Dalrymple, G.D. et al. First Report on the Acquisition of Data for Use in the Probabilistic Risk Assessment of Underground Disposal of Radioactive Wastes. U.K. DoE Report DoE/RW/86.071, 1986.

[40] Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites. Proceedings of an NEA Workshop, OECD, Paris, 1989.

[41] Grimwood, P. and Thegerström, C. Assessment of the Risk Associated with Human Intrusion at Radioactive Waste Disposal Sites. Some observations from an NEA Workshop. In Safety Assessment of Radioactive Waste Repositories; Proceedings of the Paris Symposium, OECD, Paris, 1990.

[42] Boulton, G.S. Time-Dependent Modelling of Environmental Change: The Effect of Quaternary Glaciations. In Safety Assessment of Radioactive Waste Repositories Proceedings, OECD, Paris, 1990.

[43] Laurens, J.-M., Thompson, B.G.J. and Sumerling, T.J. The Development and Application of an Integrated Radiological Risk Assessment Procedure Using Time-Dependent Probabilistic Risk Analysis. In Proc. NEA/IAEA/CEC Symposium, Paris, 1989.

[44] Foley, M.G., Petrie, G.M., Baldwin, A.J. and Craig, R.G. Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau: Results. Pacific Northwest Laboratory Report PNL-3542-2, 1982.

[45] Courbouleix, S. et al. Etude géoprospective d'un site de stockage, Vols. 1-9, Bureau de Recherches Géologiques Minières, CEC Report EUR 9866 FR, 1985.

[46] Peaudecerf, P. and Blanc, P.L. L'Evolution à long terme de l'environnement des stockages : choix des scénarios et méthodes. In Safety Assessment of Radioactive Waste Repositories, Proceedings of the Paris Symposium, OECD, Paris, 1990.

[47] Dames and Moore. Evaluation of environmental Change and its Effects on the Radiological Performance of a Hypothetical Shallow Engineered Disposal Facility at Elstow, Bedfordshire, U.K. Department of the Environment Report TR-D&M-9, DoE/RW/87.124, 1988.

[48] Dames & Moore. Background studies: climatic and geomorphological aspects of the evolution of shallow-land buried sites for radioactive waste disposal. U.K. DoE Report DoE/RW/88.055, 1988.

[49] Dames & Moore. Earthquake Effects on Groundwater Systems; An Introductory Review. U.K. DoE Report DoE/RW/89.052, September 1988.

[50] Wittingham, R.B. Human intrusion into nuclear waste repositories: a systematic approach to the definition of scenarios using human reliability modelling. In Proc. NEA Symposium, Paris, 1989.

[51] Woo, G. Is the Risk of Human Intrusion Exaggerated. In Proc. NEA Symposium Risk Associated with Human Intrusion at Radioactive Waste Disposal Sites, Paris, 1989.

APPENDIX I

List of Participants in the NEA/PAAG Working Group on Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal

This list includes all those who have attended at least one full meeting (1, 2 and/or 3) of the Group.

Jesus ALONSO (2,3)
ENRESA
Calle Emilio Vargas 7
E-28043 Madrid
Spain

Kjell ANDERSSON (1,2)
Swedish Nuclear Power Inspectorate (SKI)
Sehlstedtsgatan 11
Box 27106
S-102 52 Stockholm
Sweden

Johan ANDERSSON (3)
Swedish Nuclear Power Inspectorate (SKI)
Sehlstedtsgatan 11
Box 27106
S-102 52 Stockholm
Sweden

David E. BILLINGTON (2,3)
Theoretical Physics Division
United Kingdom Atomic Energy Authority
Oxfordshire OX11 0RA
United Kingdom

Evaristo J. BONANO (3)
Waste Management Systems
Division 6416
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185
United States

Pierre ESCALIER DES ORRES (1,2)
Commissariat à l'Energie Atomique
IPSN/DAS
CEN
B.P. No. 6
F-92265 Fontenay-aux-Roses Cedex
France

Alain CERNES (3)
Commissariat à l'Energie Atomique
IPSN/DAS
CEN
B.P. No. 6
F-92265 Fontenay-aux-Roses Cedex
France

Robert CRANWELL (1,2,3)
Safety and Reliability
Division 6415
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185
United States

Dan FEHRINGER (3)
U.S. Nuclear Regulatory Commission
Division of High-Level Waste Management
Mail Stop 4-H-3
Washington, D.C. 20555
United States

Dan GALSON (1,2,3), now with Intera Sciences, United Kingdom
OECD/Nuclear Energy Agency
Division of Radiation Protection
and Waste Management
38, boulevard Suchet
F-75016 Paris
France (Note: Attended 1st and 2nd meetings as representative of USNRC)

Bruce GOODWIN (1,2)
Atomic Energy of Canada Limited (AECL)
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba R0E 1LO
Canada

Robert GUZOWSKI (1)
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185
United States

David HODGKINSON (1,2,3) Chairman
Intera Sciences
Environmental Sciences Department
Chiltern House
45 Station Road
Henley-on-Thames
Oxfordshire RG9 1AT
United Kingdom

Michael E. STEPHENS (3)
Atomic Energy of Canada Limited (AECL)
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba R0E 1LO
Canada

Claes THEGERSTRÖM (1,2,3) Secretary, now with SKB, Sweden
OECD/Nuclear Energy Agency
Division of Radiation Protection
and Waste Management
38, boulevard Suchet
F-75016 Paris
France

Brian THOMPSON (2,3)
U.K. Department of the Environment
Her Majesty's Inspectorate of Pollution
Room A5.33, Romney House
43 Marsham Street
London SW1P 3PY
United Kingdom

Fritz van DORP (3)
NAGRA
Hardstrasse 73
CH-5430 Wettingen
Switzerland

Piet ZUIDEMA (1)
NAGRA
Hardstrasse 73
CH-5430 Wettingen
Switzerland

Acknowledgements

Contributions to the drafting and editing of this report were also received from:

David W. GEISER (supported by the U.S. Department of Energy)
Science Applications International Corporation (SAIC)
Energy Systems Group
10, rue du Conseiller Collignon
F-75116 Paris
France

Trevor SUMERLING (supported by UK Nirex Ltd.)
Intera Sciences
Chiltern House
45 Station Road
Henley-on-Thames
Oxfordshire RG9 1AT
United Kingdom

Safety Assessment of
Radioactive Waste Repositories

Systematic Approaches to Scenario Development

The analysis of the long-term safety of radioactive waste disposal systems requires the use of mathematical models and scenarios that simulate repository behaviour in response to future events. This report describes the approaches that have been developed in order to systematically identify the events and processes likely to affect this behaviour, and to construct and select representative scenarios for consideration in long-term safety studies.

(66 92 02 1) ISBN 92-64-13605-3 FF 150