Chapter 10

Status of Research On Geological Disposal for High Level Radioactive Waste in France

*Michel Raynal**

Agence Nationale pour la Gestion des Déchets Radioactifs
92266 Fontenay-aux-Roses Cedex, France

10.1 Introduction

Research programs in the field of high-level, long-lived radioactive waste management are defined and regulated by Law 91-1381 of December 30, 1991 ("the Waste Act") and its implementing decrees, particularly Decree 92-1391 of December 30, 1992 pertaining to Andra and Decree 93-940 of July 16, 1993 on underground laboratories.

The Waste Act relative to research on radioactive waste management mandates three research programs on high-level and long-lived waste management:

- separation and transmutation of long-lived radioactive elements;
- solidification processes and long-term surface storage; and
- examination of options for retrievable and non-retrievable disposal in deep geologic formations,particularly through the construction of underground laboratories.

The first two programs are relegated to the French Atomic Energy Commission (CEA) and will be conducted in the latter's laboratories. The Act confers responsibility for the third research program on Andra. In this capacity, Andra is charged with conducting a program of research and testing to examine the potential for construction of a retrievable or non-retrievable repository in deep geologic formations. Andra is also called on to participate in the other two research programs in association with the CEA.

Article 13 of the Waste Act charges Andra with long-term management of radioactive waste and "to participate in defining and conducting research and development programs on long-term radioactive waste management, in association with the French Atomic Energy Commission in particular. "

Annual progress reports on the three research programs are required (Article 4), as is an overall assessment report, *"no later than 15 years after the promulgation of this law, accompanied by proposed legislation authorizing the creation of a repository for long-lived radioactive waste, as appropriate and establishing the conditions for essential and seats relating to this repository."*

These reports, to be prepared by the National Assessment Commission, are to be submitted by the government to Parliament, which refers them to the Parliamentary Office of Science and Technology Assessment. All reports will be made public.

The decree of December 30, 1992 relative to Andra additionally stipulates that the latter shall provide the following to its oversight ministries:

- an annual report on work performed to date or to be performed in the underground laboratories to determine the suitability of deep geologic formations for radioactive waste disposal; and
- a summary report on all findings no later than December 31, 2005, accompanied as appropriate by a design for an underground repository for high-level and long-lived radioactive waste.

This Technical Activity Report by Andra reviews studies performed to date and serves as a baseline for Andra research programs to be conducted over the coming

*Currently with International Atomic Energy Agency in Vienna.

years.

10.2 What is a Deep Geologic Repository?

The purpose of geologic disposal is to contain radioactivity with a system of devices and measures that prevents radioactive materials transport to the biosphere, or at least limits it to a specified level.

Containment is based on the concept that a series of natural and artificial barriers can be placed between the source term, i.e., the waste itself, and the biosphere, listed below:

- the waste package (waste, solidification material, container and possibly overpack);
- the engineered barrier (repository structures and backfill material around the waste packages); and
- the geologic barrier (natural geologic media and access closure system).

The geologic medium plays a dual role in this scheme of things. It provides protection with respect to the source term and it protects the biosphere:

- by protecting the artificial barriers from human intrusion and the effects of weather;
- by providing a physical and chemical environment for the artificial barriers that is stable over long periods of geologic time; and
- by helping to retard and restrict radionuclide transport to the biosphere (retention, dilution before reaching the biosphere).

The three barriers in the containment system reinforce each other, with the geologic barrier playing a critical role in long-term containment. The overall integrity of the three-barrier system must be demonstrated.

Reference conditions for the multi-barrier system must be taken into consideration in two areas:

- the waste, expressed in terms of radioactive content, physical characteristics and solidification materials; and
- the geologic medium, represented by the formation and its surrounding geologic environment.

10.2.1 Waste

Generators have been generating and storing long-lived waste for several decades pending the availability of a geologic repository. Most of this waste has already been solidified in a variety of materials in accordance with regulatory requirements: glass for fission products from reprocessing, and concrete or bitumen for dry active waste. Although Andra played only a small part in the preliminary selection of materials for this type of waste in the past, henceforth it will have a larger role, as spelled out in Article 13 of the law- "Andra is charged with defining, in accordance with safety regulations, radioactive waste solidification and disposal specifications." Andra could, therefore, require the use of additional solidification materials, for example, even for waste that has already been solidified waste, or could change the cooling requirements for exothermic waste.

For purposes of long-term management, radioactive waste is differentiated by type, by activity level and by the half-life of the contaminating radionuclides it contains, based on the duration of their potential hazardousness.

Low- and medium-level, short-lived waste, called Category A waste, contains primarily beta- and gamma-emitting radioelements whose radioactive half-lives are approximately thirty years or less (such as cesium 137, cobalt 60, strontium 90, etc.). This waste, generated by routine nuclear facility operations, represents approximately 90% of the total volume of radioactive waste generated annually in France, but accounts for only 1% of its total activity. The radioactivity of this type of waste decays to natural levels in less than 300 years due to the relatively rapid decay rate of the radionuclides it contains, and it may, therefore, be suitable for near-surface monitored disposal during this time frame.

The other type of waste, which is long-lived waste and high-level waste, is divided into two categories, each of which includes long-lived waste:

- low- and medium-level Category B waste contains significant amounts of long-lived radionuclides, especially alpha-emitting transuranics;
- Category C waste contains high concentrations of both short- or medium-lived fission products and long-lived, alpha emitting transuranics.

Category C waste is highly radioactive and heat-emitting in the beginning, primarily because of its fission product contents, but this quickly declines due to the rapid decay rate of these short-lived elements. In the end, Category C waste will contain mostly long-lived elements, and represents the same types of hazards associated with Category B waste. For the most part, Categories B and C waste come from spent power reactor fuel reprocessing and from civilian and defense research and production sites of the CEA. Category B waste will also be generated during nuclear facility dismantling and must be included in waste volume estimates for disposal.

The waste volumes to be generated in the coming decades are not yet finalized due to several uncertainties, particularly:

- the amount of fuel to be used in power generation, fuel burnups, and the back-end option selected (reprocessing or direct disposal);
- potential technical advances in reprocessing, particularly in the types and volumes of waste generated; and
- method selected to solidify existing waste,

Taking a simplistic scenario — light water fuel reprocessing of 1100 metric tons of initial uranium metal per year at a burnup of 33,000 MWd/t beginning in the year 2000 — the total volume of solidified waste through the year 2020 can be estimated at 100,000 m^3 for Category B waste and 6400 m^3 for Category C waste.

Data from tests conducted as part of the other two research programs mandated by law could result in major technical shifts in solidification processes affecting the types and volumes of waste generated by reprocessing in addition to their solidification. Conversely, as data becomes available at the underground laboratory sites, Andra may identify new priorities in the other two research programs. For example, a hierarchy of radionuclides may be established in light of the retention properties of the multi-barrier system, which could establish separation and transmutation priorities for certain radionuclides. Or, Andra may develop preliminary specifications for solidification materials based on disposal conditions in deep geologic formations.

All aspects of the final waste packages must be carefully characterized to facilitate geologic repository design, Characterization must not be limited to waste volumes or to the physical, chemical and radioactive characteristics of waste packages that have been or will be fabricated; they should also include long-term behavior, failure probabilities, and their interaction with other barriers. In the case of exothermic waste, duration of storage is an essential parameter for repository design insofar as it is a factor in the waste's temperature; Andra's calculations must therefore include the date that the spent fuel that produced the exothermic waste was discharged from the reactor.

Studies of the long-term behavior of waste packages will make it possible to assess containment capacity — and possibly to find ways of improving containment — and to make sure that the waste packages are compatible with the repository concept (receiving capacity, engineered barriers ' handling, retrievability, etc.). This will result in waste package specifications that integrate both safety-related requirements and mechanical and physical requirements for waste package handling and disposal.

10.2.2 Geologic Barrier

Why dispose of radioactive waste in a deep geologic medium?

Surface disposal was rejected because the service life of any repository structures that could be built is much shorter than the half-lives of long-lived radionuclides. Moreover, it would merely postpone the problems of repository monitoring and maintenance to the future, with all the risks that that implies in the deliberately conservative scenario in which future civilizations are presumed to have neither the material means nor the technical capability to manage these problems.

Since the goal is to contain radionuclides for long periods of time, a medium with suitable radionuclide containment characteristics that evolves slowly is sought. Deep geologic formations may meet both of these criteria. There are vast areas of deep rock suitable for containing radioactive products for long periods of time.

At first glance, the low permeability and retention capacity of some of these rocks make them suitable for containing radioactive products. Enormous areas are available at depths of 200 to 1000 meters, a range that provides enough protection from surface intrusions yet does not compromise the technical feasibility of repository construction.

These available areas thus constitute physical barriers as much for the radioactive waste as for intrusions. They are also chemical barriers: water seeping through them is "buffered," acquiring geochemical properties that usually are not very corrosive through interaction with the rocks. This phenomenon is what explains how uranium deposits could subsist for hundreds of millions of years, for example. It also explains why the fossil reactors discovered in the Oklo uranium deposit in Gabon are an extraordinary illustration of the influence of the geologic medium in the repository scenario; fission products produced during "operation" of these natural reactors have remained trapped in place, contained and protected for nearly 2 billion years in an envelope of clay.

In addition, inasmuch as the excavated rock volume for a geologic repository will be a small percentage of the host rock volume (around 1%), the repository should not significantly modify the overall containment capabilities of the host rock, especially since the volume of waste to be disposed of will be even lower (around 1/10%).

Geologic evolution is slow enough to ensure containment integrity for the time necessary for the waste to undergo radioactive decay, as long as certain areas are avoided, such as those with recent volcanic activity or strong tectonic activity. Potential geologic events are limited to those that are possible in the geodynamic context of the area under considerations for example, the creation of a mountain chain during the time scales considered (around one hundred thousand years) is not plausible in a stable area such as the Parisian Basin.

To illustrate the slowness of geologic phenomena, one could also take the example of an area with a great deal of tectonic activity, such as the Messine and Calabre regions, which have risen by 1,500 to 2,000 meters in 5 million years at a geologically rapid average rate of 0.4 mm/yr.. For a stable area such as the Parisian Basin, the average estimated rates are 20 times lower, discounting the appearance of significant new discontinuities (fault fractures, etc.) in the reference time scale.

In recognizing the potential for disposal in deep geologic formations, can one therefore consider that all geologic media are valid? A consensus was quickly reached among international experts on three suitable media: granite, salt and clay. In France, the Second Castaing Commission (1984) had this to say about rejecting certain formations: *"A number of formations, known to be permeable, were rejected outright (sand, sandstone, limestone, basalt, etc.")*. However, the Commission indicated its support for an extension of the initial selection list: *"In the first phase, three types of formations were selected at the European level -granite, salt and clay - perhaps without adequately emphasizing the variety of rocks that enter into these categories. The group considers that the list of rocks resulting from clay evolution (such as shale) or even their more highly metamorphosed forms (schist and some gneiss), which are widespread rocks, should not be rejected outright."*

Nonetheless, the fundamental role of the site itself was not forgotten in this expanded list: *"It is both a series of diverse formations and the interfaces between them that make a site attractive; the same formation at another site could be determined to be completely unsuitable."* The Commission came to this conclusion: *"Potential variation in the properties of the formations, ranked by category, are so great that research must focus on specific rocks and sites as soon as preliminary screening is completed."*

However, even the cited media have different theoretical advantages and disadvantages for disposal. In addition, one medium may be more suitable than another for exothermic waste disposal. Lastly, the geologic barrier will have to be reestablished by backfilling and closing the access shaft after the repository has been constructed, and the method of doing this differs for different media.

10.2.3 Engineered Barrier

Engineered structures and backfill material for the disposal pits and the surrounding galleries separate the waste packages from the geologic medium and constitute an additional barrier which, like the natural medium, plays a dual role:

- it protects the waste packages by minimizing water contact or by creating a chemical environment that is conducive to the long-term integrity of the packages; and
- it retains any radionuclides that may have been released from the waste packages.

The design of the engineered barrier should therefore take the geologic medium and the initial radioactive content of the waste into account, in addition to the exothermic properties of certain waste packages. This applies to C waste, unless the length of its storage is to be extended, which would lead to treating C waste separately from B waste.

10.2.4 International Consensus

International organizations agree that geologic disposal is the reference solution for waste management. Other possibilities for long-lived waste management were considered, but have been rejected. Sending waste into orbit in space has been rejected as it is technically infeasible at the present time, given the volumes involved and reliability requirements. Waste burial in the earth's crust in the subduction zones of continental plates or in volcanos is not very realistic. Dilution by submersion in the sea is prohibited for long-lived radioelements by international regulations due to the risk of their return to members of the public. Burial in an ice cap was also considered; the heat of the C waste would serve melt the ice beneath each waste package, allowing it to gradually penetrate the center of the ice cap under its own weight, but implementation of this "solution" not only raises technical challenges, it also had the drawback of targeting areas that are increasingly being protected from industrial use.

France has participated in in-depth research, and an international test program has been conducted on waste burial in ocean bed sediments. Only simulated waste packages without any radioactive products were used during the program. On a technical level, and given the present state of the art, sub-oceanic burial is attractive from a safety point of view, but international legal considerations block its implementation.

Performance objectives established by the French regulatory authorities have been derived from recommendations of the International Commission on Radiological Protection (ICRP), an independent organization that analyzes the health effects of radiation exposure and develops recommendations for measures to be taken for protection from peaceful uses of artificial radioactivity. ICRP uses medical and epidemiological statistics and operating experience from a century of worldwide use of radioactivity.

Natural radioactivity comes from a certain number of radioactive isotopes that exist in nature. Natural radioactivity, and therefore exposure, varies significantly from one location on the earth to another; it varies considerably in France. Generally, the maximum allowable exposures to artificial radiation for members of the public must be less than the average exposure to natural radiation. In this very conservative approach, it is further assumed that an individual may be exposed to several different sources, and therefore, only a fraction of the allowable exposure may come from each source. The only exception to this rule is for radiation exposure for medical purposes, such as x-rays and radiation therapy, which may be much greater because the health benefits may be much higher than the related risks. ICRP recommendations are incorporated into the regulations of the International Atomic Energy Agency (IAEA) as well as into French regulations.

International organizations have been engaged in research on geologic waste disposal for some time. This was set forth in the December 14, 1990 report on high-level nuclear waste management by the Parliamentary Office on Science and Technology Assessment and is summarized below.

10.3 CHARACTERIZATION OF GEOLOGIC MEDIA

In the preceding section, deep geologic disposal is recognized as a potential solution for long-lived and high-level waste. To go one step further, specific selection criteria must be identified for the characteristics of a suitable geologic medium and site in terms of the specific use for which it is intended.

A major phase in the deep repository program involves the definition of: selection criteria, criteria ranking, determination of objectives to be achieved for each criterion, and identification of the means of verifying that the objectives are achieved in a geologic medium selected to host a geologic repository. Considerable work has already been performed in these areas in France, culminating in the June 1991 issuance of Fundamental Safety Rule (FSR) III.2.f by the Ministry of Industry's Division of Nuclear Facility Safety, whose subject matter is described as follows: "Definition of objectives to be achieved during the design and construction phase of the deep geologic repository for radioactive waste to ensure safety after the end of the repository operating period."

FSR III.2.f is the culmination of deliberations and recommendations of several advisory groups that have been working since 1983 to develop a safety-related approach to radioactive waste repositories in deep geologic formations. These include:

- working group on research and development in the field of radioactive waste management, chaired by Professor Castaing;
- working group on technical selection criteria for a geologic disposal site for radioactive waste, chaired by Professor Goguel; and
- working group on scenarios to be used in safety analysis of a geologic repository.

In addition, FSR 111.2.f takes the recommendations of cognizant international organizations into account, including those of the ICRP, IAEA, and OECD/NEA.

Two essential criteria are highlighted in the FSR: site stability and site hydrogeology. These are followed by important criteria, such as the mechanical and thermal characteristics of the medium, which determine the feasibility of repository construction, operation and closure-, and the geochemical characteristics of the media that could alter man-made barriers and determine radionuclide retention.

A minimum depth must be maintained to prevent the containment performance of the geologic barrier from being affected significantly by erosion (especially after glaciation), by a seismic event, or by the consequences of *"direct or indirect human intrusion (drilling, milling, wells, surface or subsurface construction)."* This last criteria translates into the need for geologic formations with suitable characteristics (mechanical characteristics, hydrogeology, etc.) in terms of repository safety but which also must be at sufficient depth. Lastly, there is an obvious advantage of using areas without natural resources that might attract mining activities at a later date.

10.3.1 FSR 111.2.f Criteria

The principal characteristics required by FSR 111.2.f for a disposal site for waste containing long-lived and high-level radionuclides are summarized in the following paragraphs.

Stability

"Site stability should be such that any modification to reference conditions by geologic occurrences (glaciation, seismicity, neo-tectonic shifts) must be acceptable from a repository safety perspective. In particular, stability must be demonstrated for a period of at least 10,000 years, which encompasses limited and predictable evolution. For each selected site and based on current conditions, these occurrences are to be assessed in qualitative and quantitative terms for the recent past (historical) and especially for the more distant past (Quaternary and possibly end of the Tertiary) so that the parameters characterizing these factors as well as their variations can be quantified and their influence determined. To accomplish this, it will generally be necessary to investigate the regional geologic environment of each site."

Hydrogeology

"The hydrogeology of the site must be characterized by very low permeability in the host formation and a low hydraulic gradient. Moreover, preference will be given to a low regional hydraulic gradient in the formations surrounding the host formation. Hydrogeologic measurements are to be performed in a much larger area than the repository site so as to construct flow models that factor in flows from the source to the discharge areas. The intensity and direction of underground flows can be simulated using these regional data. Discontinuities or heterogeneities which could significantly lessen the efficiency of the geologic barrier due to their type and geometry must be taken into account, and must be mapped and characterized with the greatest care so as to avoid them at the site, if necessary."

The FSR also specifies the following four criteria as being important for site assessment.

Mechanical and Thermal Characteristics

"Repository feasibility is conditioned on [mechanical and thermal characteristics], i.e., the ability to design a repository that does not significantly alter the geologic harrier. The selected repository medium must also allow for design of disposal pits that do not require access to adjust tolerances during filling operations. Research is to be performed, especially with coupled modeling of thermal and mechanical phenomena, on the influence of waste placement modes and sequences on mechanical effects in the repository, and particularly the amount of preliminary cooling and the density of waste disposal containers. This research will make it possible to determine the corresponding physical parameters and to identify the influence of these phenomena."

Geochemical Characteristics

"[Geochemical characteristics] play an important part in the long-term safety of a radioactive waste repository because they can have an effect on the alterability of man-made barriers, and they govern retention retention phenomena for radionuclides that may have been released. A quantitative description of the geochemical characteristics of the system is to be established to provide for an analysis of radionuclide transport conditions. Mineralogical analyses of the materials of the host formation are to be performed, and their geochemical evolution modeled as a function of temperature and irradiation. The role of clay minerals in particular will be studied."

Minimum Depth

"The selected site must be such that the projected repository depth guarantees that the containment performance of the geologic barrier is not significantly affect-

ed by erosion (particularly after glaciation), by a seismic event, or by 'normal' intrusion. The surface area that could be disturbed in this manner is to be assumed to be approximately 150 to 200 meters."

Depletion of Underground Resources

"With regard to underground resource management, the site is to be selected in a manner that avoids areas with a high value, whether known or suspected."

Obviously, requirements for selection of the geologic medium for the repository site are not unrelated to initial site suitability characteristics. Accordingly, the FSR specifies the following:

"The location of the repository site in the geologic formation must be:

- *in a host block devoid of large faults likely to constitute preferential sectors for hydraulic flows in a the case of crystalline media, with disposal modules to be built away from typical fracturing, although access structures could penetrate the latter; and*
- *in a medium devoid of large heterogeneities and at an adequate distance form surrounding aquifers in the case of sedimentary rock."*

10.3.2 Characterization Methodology

To supplement these rather general considerations, the FSR provides the equivalent of a scope of work for the type of investigations to be conducted, and sometimes for the methods to be employed, to characterize a site in terms of the criteria identified above. The impacts of media-specific particularities on the generic workscope are specified, as in the case of hydrogeological studies.

Crystalline Site

"For deep hydrogeology, and particularly for water transport times and discharge identification, studies are to be performed on fracturing on a variety of scales (low fracturing, hectometric fracturing, large faults bordering the host block) and on all other elements necessary for modeling."

Salt-formation Site

"For surface and lateral hydrogeology, detailed analysis of the hydrologic balance of each catchment basin is to be performed to estimate surface aquifer supply. For all aquifers, a regional hydrogeologic diagram is to be prepared showing supply areas, discontinuities, discharge areas, and interactions between aquifers as well as a hydrogeologic balance. A local hydrogeologic study is to be performed showing the geometric characteristics of the aquifers (lithostratigraphic type, morphology, continuity, etc.) and of the impermeable layers and their hydrodynamic characteristics (permeability, transmissiveness, porosity, etc.), taking into account the influence of host rock fracturing in particular and any other element necessary to quantify flows, such as local pumping. These hydrogeologic assessments are to make it possible to predict the probabilities of dissolution."

Clay-formation Site

"Surface hydrogeology is to be described at the local level to estimate surface aquifer supply. The following elements are to be determined as precisely as possible for all formations:

- *a regional hydrogeologic diagram showing source/depletion areas and the interaction between aquifers as well as a preliminary hydrogeologic balance;*
- *a local hydrogeologic diagram showing:*
  - *the geometric characteristics of the aquifers (lithostratigraphic type morphology, continuity, etc.) and of the semipermeable and impermeable levels;*
  - *their vertical and horizontal hydrodynamic characteristics (porosity, permeability, [transmissiveness, etc.), taking into account host rock fracturing in particular and any other element necessary to quantify flows;*
  - *their geochemical characteristics, particularly salinity; and*
  - *their hydrodynamic parameters and the geometry of any vertical discontinuities which could result in interactions among different stratigraphic levels."*

10.4 REPOSITORY DESIGN

The fundamental objective of the deep geologic waste repository is to protect members of the public and the environment now and in the future (FSR III.2.f).

Decree 92-1391 of December 30, 1992, concerning Andra requires that Andra submit a summary report to its oversight ministries no late than December 31, 2005 on the results of research, accompanied as appropriate by a repository design. The law clearly stipulates that the decision to create a repository is subject to numerous conditions. Foremost among these is the review of the various waste management research programs by the National Assessment Commission.

10.4.1 Performance Assessment

What tools will be used for performance assessment and how will Andra apply them to the development of its design concept?

Direct assessment of the effectiveness of the various barriers in a repository for Category B waste isn't possible due to the length of time required for containment. Long-term performance assessment depends on several scientific disciplines and follows an approach that is naturalistic, experimental and model-based to understand phenomena brought into play by the repository.

The naturalistic approach is quantitative and historical; it compares the various geologic situations observed to a historical and experimental understanding of the medium. In particular, this approach provides information on the past evolution of sites (climate, neotectonics) over time scales consistent with the radioactive decay periods of the radionuclides in the repository in order to predict future behavior.

The experimental approach provides access to host formation behavior at various locations so that: properties can be measured or at least assessed in actual conditions, disturbances to the host rock caused by the repository can be identified and ranked, behavior models can be validated and the repository concept can be adapted to the reference medium.

Modeling is a means of summarizing data from a variety of fields to understand the effects of thermo-hydro-mechanical and chemical coupling; it is used to perform sensitivity analyses and simulations.

All of these approaches are used simultaneously rather than sequentially, and all results are factored into the performance assessment.

As the last step in the process, FSR 111.2.f also requires that changes in the behavior of the repository be monitored over time: *"Given the period of time involved in repository operations and the disturbances caused during that period, specialized instrumentation is necessary to monitor changes in site and repository structural parameters. Said instrumentation is to be set up as soon as possible to ensure that the repository structure and the site are monitored not just during repository operations, but before them as well. In particular, the following should be monitored:*

- *site piezometry;*
- *deformations and more generally behavior over time of the walls of the repository that are to remain open for very long periods of time (certain reconnaissance bore holes, access shafts, service galleries);*
- *seismic movements; and*
- *thermal behavior of the medium and its effects (constraints, displacements, fracturing, etc.)."*

10.4.2 Design Concept

Having presented the regulatory and legislative context in which Andra performs research on high-level and long-lived waste disposal, the repository concept and Andra's approach to the feasibility study of the repository will be explained. Andra must first:

- identify the principal functions of the repository, which must contain the radionuclides in the waste packages, i.e., minimize and retard their potential release and migration to protect the environment and members of the public now and in the future; and
- examine the potential for waste package recovery during the period of retrievability.

To meet these requirements, the repository concept includes several elements that respond to specific objectives, particularly:

- an underground facility layout that can be adapted to the conditions likely to be encountered in deep geologic formations;
- waste placement systems; and
- radionuclide containment systems including solidified waste and geologic formations with complementary artificial barriers.

The technical feasibility of these functions requires assessment to verify that it will be possible to construct, operate and close the facilities in accordance with the requirements identified earlier while responding to the following questions:

- What constraints must be placed on the facilities due to their depth and the high temperatures generated by certain high-level wastes?

- Are there technological answers that are readily available to industry?
- Given the current limitations in knowledge and technology, what developments are necessary in the fields of mining engineering, underground handling of radioactive materials, and construction of man-made barriers?

The constraints applicable to Category C waste are different from those of B waste, which would appear to translate into specialized features for the repository. In addition to justifying the proposed technical solutions, feasibility studies are needed to identify potential requirements for additional research and development for the solutions under investigation.

10.5 UNDERGROUND RESEARCH LABORATORIES

The Waste Act designates underground research laboratories as one means of investigating the potential for retrievable or non-retrievable disposal in deep geologic formations. Andra's research objectives for these laboratories are as follows:

- perform in situ rock or fluid measurements while disturbing these materials as little as possible to understand the parameters already partially assessed during the surface reconnaissance program;
- conduct more general experiments to determine the behavior of the various rocks and fluids, taking into consideration natural phenomena and modifications caused by the construction of a potential repository as well as by the presence of waste packages;
- investigate the medium, particularly its spatial variability, to assess site suitability and the possible location of galleries and future repository excavations; and
- determine the data needed to design excavation, backfilling and closure of the disposal sites.

It should be noted that a large number of lithologic, structural, petrographic, hydrogeologic, thermomechanic and tectonic characteristics are already available at the surface, which make it possible to analyze them in a regional context and conduct a preliminary assessment of the suitability of the site to host a repository. This preliminary assessment will be expanded and supplement ed by investigations in the underground laboratories. Surface and underground work can be conducted in parallel rather than sequentially.

The Waste Act and its implementing Decree 9340 of July 16, 1993, specify the conditions under which laboratory construction and operation will be licensed. The sheer size of the laboratories makes them true industrial projects. There will be complete openness in the methodology used, as set forth in FSR III.2.f, which identifies essential and important criteria for site characterization and specifies general requirements for site investigations in Appendix 1.

The primary purpose of the measurements and tests to be conducted on site and in the laboratory is to confirm the initial assessment of the site's qualities and drawbacks and the overall adequacy of the selected location. In addition to initial measurements and tests, phenomenological studies and tests in the underground laboratories, along with research of a more fundamental nature in conventional laboratories, will help Andra to assess the site behavior in more depth and detail that results from the disturbances to which it has been exposed during construction and disposal.

It should be noted that validation of the complex approach described above involves an experimental period that cannot be cut short, followed by interpretation of test results, which translates into a rather tight schedule.

10.6 ANDRA RESEARCH PROGRAMS

10.6.1 Research Budget and Participants

Andra has embarked on a vast research program in furtherance of its missions, as reflected in this report and in the large budget and numerous contractors reporting to Andra. The 1993 deep disposal research budget was FF 250 million francs for planning activities alone.

The size of the subcontractors varies widely; some research is so specialized that sometimes only a university laboratory or a single engineering company can respond. On the other hand, it is sometimes necessary to turn to large groups such as BRGM [French Geological Survey], CEA [Atomic Energy Commission], EDF, MDPA, Bertin, Cogema, and others. Andra controls the research objectives, of course, but may also select the laboratory within these organizations that is best suited for the work requested.

The Agency's research and development programs are scrutinized by its Scientific Council, who:

- issues, opinions and recommendations on scientific

and technical objectives and on costs,
- is kept informed on progress, and
- assesses the results of these programs.

The opinions, recommendations and report of the Scientific Counsel are submitted to Andra's Board of Directors. Andra's research results for the year are set forth in its annual report on research and development, presentations by Andra and its suppliers at international conferences, and articles by Andra and its suppliers in the trade press. Whenever work funded by Andra needs to be protected legally for commercial use, patents are registered and other forms of protection are adopted.

CHAPTER 11

GEOSCIENTIFIC AND ROCK MECHANICAL ACTIVITIES FOR THE RADIOACTIVE WASTE REPOSITORIES IN GERMANY: KEY ISSUES, STATUS AND FUTURE PLANS

M. Langer[1], *and H. Röthemeyer*[2]
1. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany
2. Bundesamt für Strahlenschutz, Salzgitter, Germany

Abstract. The engineering geological and rock mechanics activities for radioactive waste repositories are strongly linked to the safety concepts for the repository projects. Key issues are: proper site characterization, proof of geotechnical safety and quantitative description of geochemical processes and of geological scenarios for long-term safety assessment calculations. A status report of the German repository projects Gorleben and Konrad based on this concept will be presented. While these projects are still being pursued the former Morsleben salt mine in Sachsen-Anhalt, which was used as a repository for short-lived low and intermediate level waste from 1981 until 1991 has resumed its operation in 1994. In the paper some issues are demonstrated by an example: site characterisation work for a salt dome, geotechnical measurements and calculations to proof the stability of a mine, and considerations of geomechmical natural analog for calibration of constitutive laws. For the future the role and contributions of geoscientific and rock mechanics work within the safety assessment issues (e.g. geomechanical safety indicators) must be identified in greater detail.

11.1 INTRODUCTION

Since the early sixties, the radioactive waste disposal policy in the Federal Republic of Germany has been based on the decision that all kinds of radioactive waste are to be disposed of in deep geological formations. The basic aspects which must be taken into account to achieve this objective of disposal are compiled in the "RSK-Sicherheitskriterien für die Endlagerung radioaktiver Abfälle" (Safety Criteria for the Disposal of Radioactive Waste in a Mine). The following criteria are considered to be the most important ones:

The required safety of a repository constructed in a geological formation must be demonstrated by a site-specific safety assessment which includes the respective geological situation, the technical concept of the repository including its scheduled mode of operation, and the waste packages intended to be disposed of.

In the post-closure phase, the radionuclides which might reach the biosphere via the water path as a result of transport processes not completely excludable must not lead to individual dose rates which exceed the limiting values specified in section 45 of the German Radiation Protection Ordinance (0.3 mSv/a concept).

11.2 GEOTECHNICAL SAFETY

Natural geological and geotechnical barriers are an important part of a multiple-barrier system. Thus, the loadbearing capacity of the rock (expressed, for example, through subsidence or cavern stability), its geological and tectonic stability (e.g. mass movement or earthquakes), and its geochemical and hydrogeological development (e.g. groundwater movement and the potential for dissolution of the rock) are important aspects of the safety analysis. Therefore safety cannot be assessed from a purely engineering point of view, but must include geological factors. A site-specific modelling of geotechnical and geomechanical features and processes is needed.

The safety analysis must be based on a safety concept that includes the possibilities of failure (failure scenarios) that could occur during the excavation, operation and post operation phases, as well as measures to avoid such failures. Monitoring is also a part of the safety concept.

11.2.1 Geotechnical safety plan

The site specific geotechnical safety plan has to include the individual dose/risk scenarios and possible contingencies for which again measures and/or verifications are required. The safety plan has to be updated as new experience becomes available (e.g. during the construction or during the operation of the plant) The safety plan for an underground disposal plant (disposal mine) should, inter alia, describe the following (Langer et at 1993):

- measures to avoid or reduce risks;
- possible actions to enhance stability of the plant-based on monitoring systems; and
- acceptable residual risks.

The potential risks define the limiting situations which are to be avoided. These could be for example:

- local fractures in mine openings;
- failure of pillars and roofs;
- rock burst;
- rock mass loosening due to large cavity or shaft convergence, leading to a loss of integrity of the rock mass; and
- loss of functionality of seal structures(e.g. dams).

The safety plan should assess the following:

- system failure of load bearing structures;
- long term integrity of geological barriers; and
- seal functions of seal structures.

To this end the following measurements and/or calculations are available:

- the short term and long term convergence of cavities;
- large scale deformations in rock mass and neighbouring rock and overburden; and
- stress states in rock mass.

11.2.2 Numerical proof of geotechnical safety

The potential risks as described in section 11.2.1 which generally represents states of a hypothetical character and are hence not covered by the in situ measurements are to be checked mathematically. Relevant models have to be developed for each situation, and are to comprise the following component sections:

- presentation of the dose/risk scenario under investigation;
- effects such as primary state of rock mass, temperature, cavity convergence, effects of waste, earthquake, etc;
- calculation model which must cover rock mass formations, cavities and their changes as realistically as possible;
- material models for rock mass and overburden, and possibly also waste and backfill;
- calculation of safety relevant status variables such as deformations, stresses, and possibly permeability of liquids (and gases);
- checking and assessing calculation results; and
- safety concept which provides statements as to threshold values for risks.

The informative value of the theoretical proofs is decisively influenced by the expressions introduced into the calculation model. For this reason it is necessary to be aware of these influences when assessing safety matters. These include, inter alia:

- show sources of errors e.g. in the structural description of the disposal facility, in the material laws, in the numerical calculations methods; and
- show the sensitivity of the results to changes in the input parameters by calculating with parameters variations (e.g. also to identify natural scatter).

In the practical performance of the proofs it may be useful to initially work with assumptions which are unequivocally conservative which produce simple verification methods and then move on to more complex expressions in places where the conservative calculations indicate possible critical states. When using this procedure of simplified verification the conservativeness of the expressions must be thoroughly evaluated.

Uncertainties are for example:

- variation of material properties with respect to space and time;
- uncertainties in the determination of the load;
- inexactness of the model (simulation of the physical and geological conditions); and
- efforts of unexpected and/or possibly omitted events.

Geological and geotechnical uncertainties can be mastered by a method of calculated risk ("Geoengineering

Confidence Building", see Fig. 11.1). The main part of this method is the handling and validation of models (Langer, 1994).

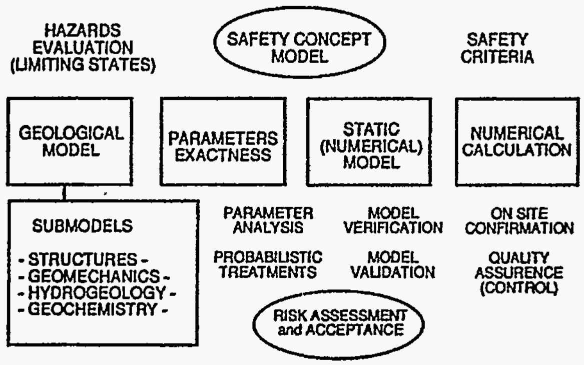


Figure 11.1. Geo-engineering safety confidence building.

11.3 GORLEBEN REPOSITORY PROJECT

11.3.1 Site investigation and planning

The Gorleben salt dome has been under scrutiny since 1979 to host a repository at depths between 840 and 1200 m, mainly for high level and/or alpha bearing wastes and spent fuel. Site investigations and planning are at present based on a nuclear capacity of 2500 GWa, leading to a total activity of about 10^{21} Bq and an alpha activity of about 10^{19} Bq (Brennecke et al., 1994). The following work from above ground was carried out between 1979 and 1985 to investigate the geology and hydrogeology of the Gorleben site:

- 4 boreholes, each about 2000 m deep, for investigation of the salt dome;
- 44 boreholes for investigation of the cap rock and the underlying salt beds;
- 2 preliminary boreholes for the shafts Gorleben I and Gorleben 2;
- 156 km of seismic profiles;
- 145 investigation drillings into the Cenozoic cover;
- 326 drillings for the installation of piezometers;
- 4 long time pumping tests (pumping time about 3 weeks for each test); and
- 1 borehole for investigations of the Palaeogene in the rim syncline.

Other investigations which were carried out include geoelectrical and geothermal studies, gravimetry, seismology, geochemistry, isotope geochemistry, and micropalaeontology.

The objective of the exploration from underground is to acquire all information needed to evaluate the operational and long-term safety of the planned repository. This has to be achieved while keeping disadvantages of potential damage to the geological barriers as low as reasonably achievable. Two shafts have been erected. Subsequently two pairs of exploratory drifts, connected by eight cross-cuts, will be driven to the northeast and southwest in a depths of 840 m. From there, numerous exploratory wells (in total about 60 km) will be drilled horizontally and vertically up to about the outer boundary of the prospective repository fields.

The stratigraphy and structure of the salt dome will be investigated by geological, geophysical and petrographic methods in such detail that it will be possible to identify rock salt sufficiently large and otherwise suitable for the different types of radioactive waste. Also, the positions of the more problematic layers, such as the main anhydrite and the Stassfurt potash seam, as well as brine pockets and gas-bearing salt bodies, will have to be determined exactly for proper risk assessment.

11.3.2 Results

In agreement with the international approach (IAEA, 1994), remarkable results were recently achieved in the use of safety indicators for the barrier performance of rock salt in general, and of the Gorleben salt dome in particular:

- An empirically tested exponential mass change model predicts isolation potential of repositories in rock salt of millions of years. The results from the site investigations in Gorleben are in agreement with these predictions (Röthemeyer, 1991).
- This evidence is supported by site-specific natural analogues. The analysis of fluid inclusions gave evidence of the depth down to which the glacially influenced subrosion processes effected the salt dome, and proved a past isolation period of 2.5 x 10^8 years at the depths of 860 to 1360 m envisaged for waste disposal.
- Regarding the halokinetic process of the Gorleben salt dome, the average rate of uprise of salt in the top part of the salt diapir has been calculated. The diagram (Fig. 11.2) shows a rapid increase in the rate of uprise from the beginning of piercement to a culmi-

nation in the Cretaceous, and a gradual decrease in the rate up to the present day. Jaritz (1991) plotted curves of the variation in the rate of uprise with time using Zirngast's figures. He obtained values of 0.07 to 0.08 mm/a (Fig. 11.2) for the maximum rate of uprise of the salt, using different time scales. This is slightly lower than the other salt diapirs in NW Germany, for which Jaritz gives values between 0.1 and 0.5 mm/a. Both curves agree as to the present rate of uprise (0.01 mm/a). In the light of the more or less constant dynamic conditions, on which the supply of fresh salt from below depends, it is possible to predict that in the future the rate of salt uprise will not change significantly for at least one million years. Thus, assuming a rate of uprise of about 0.01 mm/a, uprise over the next 10,000 years will amount to 10 cm and over the next 1 million years, about 10 m.

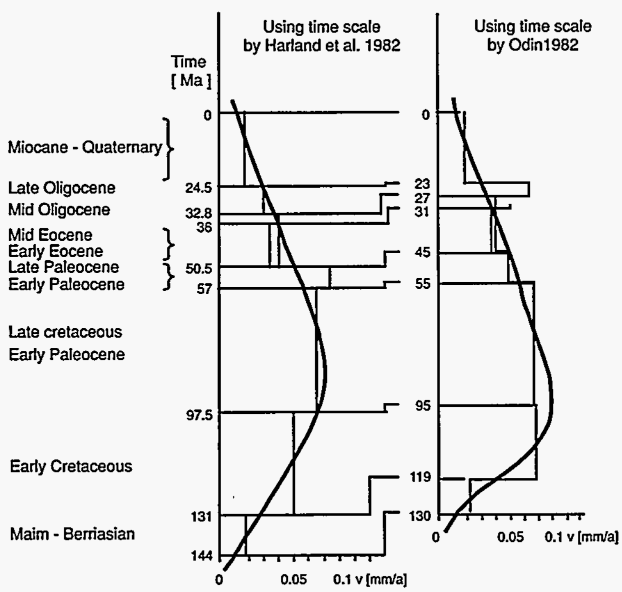


Figure 11.2. Mean rate (v) of uprise of the salt at the top of the salt diapir, after ZIRNGAST in JARITZ, 1991.

- The effect of future geological processes have been considered with probalistic modelling of structural response. As an example, impact of a temperature decrease during glacial age on the integrity of the salt barrier above a repository has been analysed. A sensitivity study showed that besides the depth of the salt dome, also the shape of the dome and the stiffness of the adjacent rock have a significant influence on the development of tensile stress at the top of the salt dome. However, creep capacity of rock salt enables the salt formation to significantly reduce the total amount of tensile stress. Even under very conservative assumptions, thermally induced fractures will only develop as far as about 100 metres depth, and therefore will not endanger the barrier function. With respect to the computational procedure, it has to be mentioned that the linear approach to the system response surface is valid for the case in question but can be insufficient for other evaluations. A nonlinear approach would be recommended. Respective development is under progress (Wallner and Eickemeier, 1994).

- Regarding the rock mechanical properties of the rock salt from Gorleben dome, the creep behaviour has especially been investigated. The application of improved experimental techniques, as well as examination of our extensive data base, show that the specific textural characteristics of the various types of rock salt cause significant differences in creep behaviour. In spite of the same experimental stress and temperature conditions, samples yield steady state creep rates that vary from each other by a factor of more than 10. Differences of up to a factor of 100 have even been recorded from rather pure rock salt (greater than 95% halite). Figure 11.3 illustrates a summary of the experimental results for steady state creep rates at room temperature, which were obtained on rock salt samples from the Gorleben salt dome. These suggest that there is a large range of creep characteristics. The "locally" large differences (factor of 100) are rarely taken into consideration during modelling calculations, and consequently the results are not particulary reliable. The results shown in Figure 11.3 also confirm the "miners law" in that the "older halite" (z2) on average creeps faster than the "younger halite" (z3). Two formulae for steady state creep (BGR2 and BGRb) have been determined. In Figure 11.3 the BGRa law is located in the upper domain for the creep rates, and the BGRb law in the lower domain. Both formulae yield a stress exponent n= 5 for the stress sensitivity. Miroscopic impurities are the main reason for the large differences in creep. It is known from material science that it is not the overall mass-proportion of impurities but the number, distribution and type of particles that affects the ductility. This is easy to comprehend, since every defect in the crystal lattice is an obstacle to the moving dislocations (Hunsche and Schulze 1994).

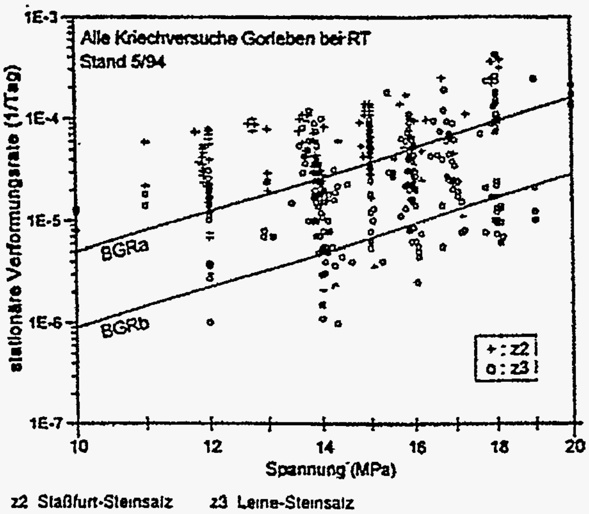


Figure 11.3. Stationary creep rates of salt cores from Gorleben.

11.4 KONRAD REPOSITORY PROJECT

11.4.1 Safety assessment and planning

It is intended to emplace into the Konrad repository - an abandoned iron ore mine in the southeast of Niedersachsen - radioactive wastes which exert a negligible thermal influence on the host rock (total activity 5 x 10^{18} Bq, alpha activity 1.5 x 10^{17} Bq). The application for the initiation of a licensing procedure for the Konrad repository project was filed in 1982. A decision on the project is expected for the near future.

New cavities of about 10^6 m^3 volume will be driven at depths between 800 and 1300 m for the emplacement of the waste. A time of operation of at least about 40 years is expected, depending on the amount of waste to be disposed of annually.

Because of the licensing autbority's opinion on long-term safety, limitations will arise to 7.0 x 10^{11} Bq for ^{129}I and 1.9 x 10^{12} Bq for ^{238}U. Due to the long travel times from the repository to the biosphere, a potential radiation exposure of the biosphere will only result in the case of long-lived radionuclides like ^{129}I and ^{238}U with its decay products, and only after hundreds of thousands of years and several million years, respectively. These results are taken from model calculations for radionuclide migration in the repository's near and far field. Since the potential radiation exposure will occur far beyond a time limit for which it may be assumed with sufficient reliability that the marginal conditions like the present geological and hydrogeological situation at the site underlaying the calculations are still valid, the results obtained for individual doses only have the purpose to judge the isolation potential of the site. This opinion of the applicant was discussed controversially within the licensing process. More details were presented by Röthemeyer (1993).

11.4.2 Rock mechanics work

Among others, the following types of measurements have been carried out:

- measurement of subsidence at ground level using leveling;
- measurement of the drop in roof level in the main levels;
- measurement of the convergence in the main levels and exploratory drifts;
- measurement of rock mass deformation above a former working field (flushing field); and
- measurement of rock stresses.

Subsidence was measured using precision levelling on a fixed network of 390 points distributed over approximately 40 km^2. The results of these measurements may be summarized as follows:

- The first subsidence occurred approximately one year after the start of mining.
- The maximum subsidence of the trough is in the area above the flushing field. In May 1985, 20 years after the start of mining, the subsidence here totaled 264 mm. The subsidence trough had a limiting angle of between 35 and 39°.
- During ore extraction the maximum rate of subsidence over the southern field was 2.8 mm/month; in 1985 this had reduced to only 3 mm/year.

The development over time of the subsidence of levelling points does not indicate any irregulatrities. The trough is subsiding uniformly.

Overall, the subsidence may be considered as small. This is confirmed by the fact that no damage has been observed at the surface. The measurement results allow the assumption to be made that subsidence is close to its final value. A large number of convergence measurement stations were set up on the main levels and exploratory drifts. It proved in part possible to carry out initial measurements very soon after cavity excavation.

The evaluation of the convergence measurements has provided the following results:

1. The convergence processes observed in the Konrad mine are not based on creep processes, as in rock salt, for example. They are rather related to microfissuring processes in the nearby surrounding rock, which lead to deconsolidation of the rock mass.
2. The convergence of the drifts over time may be described using a logarithmic function (Fig. 11.4).
3. The convergence behaviour of the drifts is dependent upon the degree of excavation; the higher the degree of excavation the higher the convergence.
4. The floors of the drifts frequently show greater convergence than the roofs.
5. In drifts which pass through old mine sections the effects of stress redistribution in the area of the old workings are continuing.

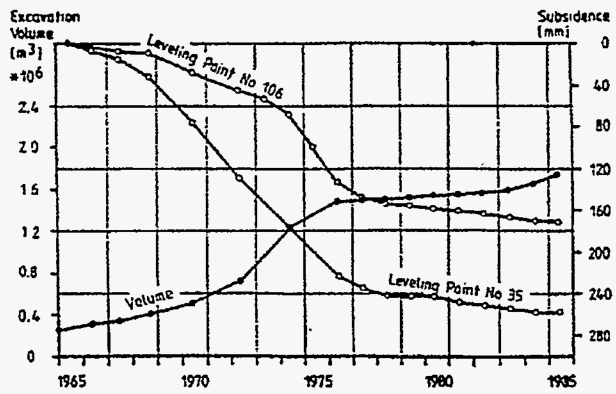


Figure 11.4. Subsidence and excavation volume versus time, Konrad mine.

In addition, numerical calculations were executed to assess the rock mechanical processes in the overburden and the stability of the repository. The calculations were carried out using the Finite Flement Program System ADINA.

Primary stress measurements were carried out in two boreholes at borehole depths of approx. 15 m to 25 m. The results are plotted in Figure 11.5. The maximum and minimum stresses are shown as functions of depth of the borehole under study. The measurements allow maximum values of between approx. -18.0 and -24.5 MPa to be read, and minimum values of between approx. -12.0 and -17.6 MPa. The overall averages are -21.0 MPa (maximum values) and -14.8 MPa (minimum values). The maximum stresses are generally subvertical (±20° to ±30°) in orientation.

Typical results measured for secondary stresses normal to plane of bedding me given in Figure 11.6 for measurement section MQ4 in the pillar between chamber 231S and chamber 241S. Here the measured stress changes were raised by the amount of the theoretical primary stress. The measured values show a marked drop as distance from wall increases. At approx. 10 m distance stress changes have fallen to minor levels.

As a comparison the results of the numerical model calculations are shown. These model calculations are reported in detail in Dickmmn et al. (1991). As Figure 11.6 shows, there is good agreement between measured and theoretical secondary stresses.

Generally, the rock mechanics tests undertaken at the Konrad drift system in field 5/1 have as their most important result that the construction of storage chambers in middle Jurassic coal oolite for radioactive wastes generating low levels of heat with cross sectional areas of 40 m^2 and chamber separations of approx. 35 m can be safely carried out from a rock mechanical point of view. The results of the geotechnical measurements performed in test field 5/1 do not indicate my risk to stability of the hard rock and the drifts.

With respect to the test techniques under the difficult *in-situ* conditions in the underground, the instrumentation proved itself for the most part very well and produced reliable results. The test concept of overlapping and complementary test methods has proved itself to be constructive and expeditious.

11.5 MORSLEBEN REPOSITORY

Short-lived low and intermediate level radioactive waste from the operation of nuclear power plants and the application of radionuclides in research, medicine and industry in the former Geman Democratic Republic was disposed of in the Endlagerung für radioaktiver Abfälle Morsleben (ERAM, Morsleben repository for radioactive waste) an abandoned salt mine located near the village of Morsleben (now in the state of Sachsen-Anhalt).

Until 1969, this mine had produced potash and rock salt. The salt was excavated in room and pillar mining down to a depth of about 500 m so that mine openings result-

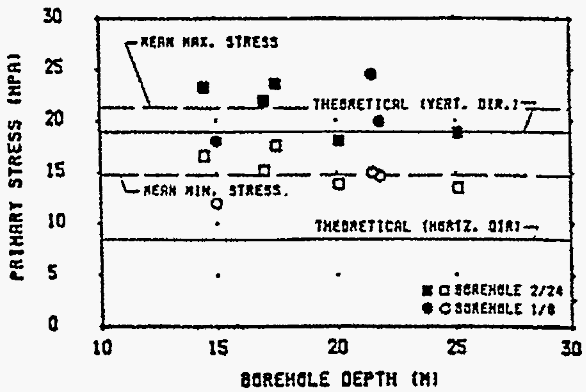


Figure 11.5. Primary stresses in test field 5/1.

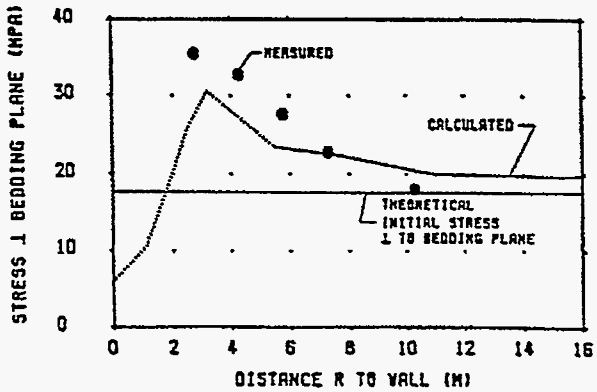


Figure 11.6. Secondary stresses normal to plane of bedding.

ed with a maximum length of about 150 m and a maximum width and height of about 30 m, respectively. In total, a volume of about 7.6 x 10^6 m^3 was excavated and partly backfilled (2.1 x 10^6 m^3,). Since the first operational license was granted in 1981, the repository has been used for the emplacement of short-lived low and intermediate level waste without the intention of retrieval. Spent radiation sources were also disposed of in this facility.

Until 1991, radioactive waste with a total emplacement volume of approximately 14,500 m^3 and about 6,200 radiation sources were disposed of. In total, an activity of 1.8 x 10^{14} Bq was emplaced. The activity of alpha emitters amount to 1.6 x 10^{11} Bq, and the activity of beta/gamma emitters, to 1.8 x 10^{14} Bq. The waste was mainly delivered by combined rail-and-road transports using standardized freight containers. About 2,900 such containers were delivered until 1991.

Since the German Unity in October 1990, the Morsleben facility has the status of a federal repository. The operating license is limited by law until June 30, 2000. Emplacement of waste has been resumed in January 1994. Until the end of the year 1995, 5,691 m^3 of waste with the total activity of 2.6 x 10^{13} Bq [(α: 1.4 x 10^{10} Bq] has been disposed of.

11.6 FUTURE RESEARCH WORK

The European Commission has recently performed a review study on the status of understanding of thermal, mechanical, hydrogeological and geochemical properties of host rock formations (Balz, 1995). In general, it was concluded that the large number of heating experiments which have been performed, both in laboratory and in the field, have provided sufficient knowledge about the nature of the purely thermal aspects and existing models seem to be adequate for predicting the resulting temperature field and its evolution with time.

It becomes more difficult when one has to consider the influence of temperature increase on the mechanical, hydrogeological and geochemical properties and in particular to understand and perform predictive modelling of coupled effects.

Therfore, it has also been recognised that the couplings

Table 11.1. Recommendations for research

Priority 1
• Further development of investigation and interpretation methods for coupled geochemistry/geomechanical/brine migration models.
• Further studies of geomechanical properties with gas and brine related parameters as variables.
• Development of consistent thermomechanical models and relevant codes for backfill material.
• Scientifically based engineering studies to develop performance criteria for backfilling and sealing techniques.
• *In-situ* studies of the gas problem.
Priority 2
• Comparison of stress measurements methods and interpretation procedures, taking salt creep into account.
• Development of a freshwater/brine groundwater flow model, and validation under *in-situ* conditions.
• Development of models for generation and transport of gases and brines.
• Optimization of "geoprospective" natural analogue, scenarios and palaeohydrological methods.
• Testing of backfilling techniques in a URL.

of chemistry with thermo-hydromechanical (THM) processes of the various host rocks is a crucial issue which has to be further investigated.

Another subject which has gained attention in recent years is the issue of gas generation and transport and possible impact on operational and long term safety. In any repository for radioactive wastes, gases will be formed due to corrosion of metals, microbial degradation of organic matter and to a lesser extent from radiolytic decomposition of water and organic compounds. As a consequence, gas pressure will build up in the near field until it is released through the system of engineered barriers into the geosphere at a rate equivalent to the production rate. Research efforts have been undertaken to assess the rate of production for various waste forms, disposed of in various host rocks. Moreover, models have been developed for describing gas transport and/or two phase flow through the geologic formations. However, more research is needed for a better understanding of basic mechanisms of gas and/or two phase flow through the host rock or along preferential pathways, fractures and faults. Site specific data are necessary for the assessment of the possible impact of gas generation on repository safety. Technical measures are available or further being developed to cope with these issues by appropriate repository design.

Reflecting these results and considering the following key questions:

- can a candidate respository site be adequately characterised (availability of site characterisation techniques and methodology)?
- are thermal, hydrogeological and mechanical properties and processes of salt formations well enough understood (long-term efficiency of the geological barrier)?
- will it be possible to build, operate, backfill and seal a repository in salt rock in a safe and economic way (repository design aspects)?

Conclusions for further scientific work have been given (Langer, 1995). Regarding rock salt as host rock the recommendations listed in Table 11.1 can be given. The aim of this research work is to assure that appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

REFERENCES

Langer, M., et al., Empfehlungen des Arbeitskreises Salzmechanik zur Geotechnik der Untertage-deponierung, Bautechnik 70: 734-744, 1993.

Langer, M., Geoscientific evaluation of geological and geotechnical barriers with respect to waste disposal projects, Proc. 7th Int. IAEG Congr. 2827-2935, Rotterdam, Balkema, 1994.

Brennecke, P., et al., Final disposal in Germany, Kerntechnik 59: 23-27, 1994.

IAEA, Safety Indicators on different time frames for the safety assessment Tec. Doc. 767, Vienna, 1994.

Röthemeyer, H., ed., Endlagerung radioaktiver Abfälle, VCH Verlag Weinheim, 1991.

Jaritz, W., Die Entwicklungsgeschichte des Salzstocks Gorleben, Geol. Jb A 132: 3-31, 1991.

Wallner, M. and R. Eickemeier, Modelling of consequences of future geological processes by means of probabilistic methods, NEA-Workshop on Site Evaluation (SEDE), Paris, 1994.

Hunsche, U. and O. Schulze, Das Kriechverhalten von Steinsalz, Kali u. Steinsalz 11: 238-255, 1994.

Röthemeyer, H., Aspects of a confidence building process in long term safety evaluation for HWL-repositories, Proc. Int. Conf. Safe Waste, Avignon, p. 290, 1993.

Diekmann, et al., Geotechnical measurements during excavation of parallel drifts, 3rd Int. Symp. Field Measurements, Oslo: 561-570, 1991.

Balz, W., Research and development on radioactive waste management, In: IAEA Tec. Doc. 853, 72-87, Vienna, 1995.

Langer, M., Review of R&D requirement on THM properties of salt, In: CEC Proc. Workshop, Testing and Modelling of thermal, mechanical and hydrogeological properties of host rocks, 223-250, Brussels, 1995.

Chapter 12

Hungarian Approach For Final Disposal Of High Level Radioactive Waste

P. Ormai[1], F. Frigyesi[1], I. Benkovics[2], L. Kovács[2], J. Csicsák[2], Gy. Majoros[2] G. Érdi-Krausz[3] and Gy. Bárdosi[4]

1. Paks, Nuclear Power Plant Ltd., 7030 Paks P.O. Box 71, Hungary
2. Mecsek Ore Mining Company, 7633 Pécs P.O. Box 121, Hungary
3. Mecsekuran Ltd., 7614 Kövágószölös, P.O. Box 65, Hungary
4. Corresponding Member, Hungarian Academy of Sciences, 1055 Kossuth sq 18, Budapest, Hungary

12.1 Introduction

In Hungary, nuclear power provides a substantial portion of the total electricity produced in the country. The Paks Nuclear Power Plant (NPP) contains four VVER-440 nuclear reactors, each capable of producing 460 MW of electricity. This plant regularly produces more than 40% of the electricity consumed in Hungary. There is currently no plan to increase the electrical generating capacity of Hungary, but if future additions to nuclear-based electrical generation were to be made, they would significantly increase nuclear power's share of electricity consumed.

Fuel for the Hungarian NPP, as is the case for all other East European VVERs, has been supplied in the past by the ex-Soviet Union. As part of the fuel agreement, the Soviet Union was obliged to take back and dispose of all spent fuel (using another supplier would leave Hungary with the problem of high level waste disposal). In the past, Hungary was glad to have the problem of disposal dealt with in this way. Now, although contracts for fuel supply and return are still in force, Hungary is less certain how long this "comfortable arrangement" will last.

The shipment of spent fuel for 1992 was ready for dispatch but has been delayed due to problems with transport through the Ukraine. It is understood that Russia, while they may still be prepared to take and process spent fuel, will now send the high level waste back to Hungary for disposal. The cost of such disposal will be charged to the Paks NPP operation and, therefore, future costs are likely to increase.

This likely interruption of the current spent fuel disposal route may lead to a fairly immediate problem in Hungary. The spent fuel ponds will be totally full by the end of refueling in 1995. It is therefore necessary for a new program for removal of fuel from the ponds to be implemented before the 1996 refueling to avoid the necessity to shutdown the reactors.

The current intention is to build an interim storage facility to hold spent fuel after it has completed five years of cooling in the ponds. In 1993, a decision was made to construct a Modular Vault Dry Store at Paks based on the GEC Alsthom design, which was first used at Fort St. Vrain (USA). At some point in the future, the fuel would either be packaged for direct disposal, or reprocessed outside the country and the high level vitrified waste returned to Hungary for disposal.

As insurance against the waste remaining in Hungary or being returned after reprocessing, it is highly desirable to proceed by planning for possible disposal of spent fuel some 50 years or more in the future.

Normally, the siting of any HLW repository should be started by screening the entire country for suitable locations. However, as a result of preliminary investigations, Hungary has a geological formation that is considered at least as a national "treasure." This is a siltstone, an Upper Permian red-colored formation, covering some 150 sq. km. Its thickness from borehole drilling is about 800-900 m.

Based on preliminary assessments and technical considerations, the use of the Permian Boda claystone formation in the Mecsek Mountain area is being considered for HLW disposal. To evaluate the suitability of this formation as a location for a waste repository, investigations have started with the technical assistance of the Atomic Energy of Canada, Ltd.

12.2 SPENT FUEL CHARACTERISTICS

The radioactivity and heat output of a spent Paks NPP fuel assembly is similar to spent fuel assemblies from other pressurized water reactors for the same burnup. However, the geometry and components of these fuel assemblies are different from those of fuel assemblies from other pressurized water reactors. Two types of fuel assemblies are used in the Paks NPP, the operational assembly and the follower part of the absorbers. Both types have a hexagonal cross section with a key dimension across the flat side of the hexagon of 144.2 mm.

Each assembly contains 126 fuel rods in a hexagonal array and surrounded by a hexagonally shaped tube. This tube is fabricated from an alloy containing 97.5% zirconium and 2.5% niobium. The fuel rods consist of UO_2 pellets contained in a tube made from a 99% zirconium and 1% niobium alloy. The inside and outside diameters of the cladding tube are 7.72 mm and 9.15 mm, respectively. The assembly top head, nozzle units and spacers (10 per assembly) are made from stainless steel. The overall length of the operational fuel assembly is 3,217 mm and the active length is 2,470 mm. The total weight of the operational assembly is 215 kg, which includes 120.2 kg of fissile material. The differences between the Paks NPP fuel assembly and a typical pressurized water reactor fuel assembly would not preclude direct disposal of the spent Paks assemblies in a repository.

Assuming a 30-year operational life for each reactor unit and no change in the fuel cycle, 15,316 spent fuel assemblies will be discharged from the Paks NPP.

12.3 OPTIONS FOR SPENT FUEL MANAGEMENT

Paks NPP Ltd. had two contracts with the Soviet Union (now Russia): one, on the governmental level, addressing the fresh fuel supply; and the other, a private, low-level contract covering the shipment of spent fuel back to Russia. Furthermore, in April 1994, a new protocol was signed between the governments of Russia and Hungary complementing the earlier governmental contract. The protocol confirmed that the fresh fuel for Paks NPP will be supplied by Russia, and Russia is ready to receive Hungarian spent reactor fuel. In spite of the new protocol, the Hungarian government was not able to ship spent fuel to Russia in 1994. Because of current difficulties and the fact that the protocol does not contain a guarantee that Hungarian spent fuel will be returned to Russia, there is a very low probability that long-term shipment of Paks NPP spent fuel to Russia will be realized. Therefore, it is assumed that in the long term, the return of spent fuel to Russia will not be possible.

The Hungarian government and Paks NPP Ltd. had to consider developing a program to manage the spent fuel assemblies from the existing Paks NPP and from any future nuclear power placed in operation in Hungary. This program would be similar to spent fuel strategies of other small VVER operators, such as the Czech and Slovak Republics and Finland. It is also consistent with the current international tendency of each country operating nuclear reactors to develop an independent high-level waste management strategy for storage and disposal.

The options available to Hungary for the management of spent fuel include: reprocessing, direct disposal or a deferred (wait and see) decision between these two options. In the latter case, the spent fuel would be stored in Intermediate Spent Fuel Store (ISFS) for approximately 50 years. Each of these options, for the backend of the fuel cycle, requires a geological repository for disposal of HLW. For the reprocessing option, the waste forms would be vitrified fission products, plutonium waste (if mixed oxide fuel is not acceptable) and eventually fuel assemblies (when the fissile material can no longer be recycled). For the direct disposal option, the waste form would be one or more types of spent fuel assemblies in containers. For the wait and see option, the waste form will depend on whether reprocessing or direct disposal is selected as the management strategy at the end of the storage period.

12.4 GEOLOGICAL FORMATIONS TO BE EVALUATED

The long-term management of high-level radioactive waste has only recently become an issue in Hungary. Concurrent with the attempts to return spent fuel to Russia, a decision was made to erect an ISFS at Paks NPP, and this facility is now being constructed. The decision concerning the spent fuel management option at the end of the interim storage period has not been made.

Because of the geology of Hungary, only a limited number of potentially suitable disposal sites for high level waste are available within the country. One of these is a Permian claystone deposit called the Boda Claystone Formation near the city of Pécs in Southwestern Hungary. The uranium mine is located in a Permian sandstone formation close to part of this claystone formation. The formation has also been investigated as a potential host for low-level waste disposal. When high-level disposal became a concern for Hungary, the Mecsek Ore Mining Company proposed that the Boda Claystone Formation, of Permian age, be investigated for its suitability as host rock for a Hungarian nuclear waste repository. Information about the lithology and structure of the overlying sandstone has been collected during uranitun mining over the past 40 years.

Useful information about, the groundwater flow conditions of the sandstone has also been collected from the mining operations. About 50 boreholes were drilled from surface to investigate the uranium deposits in the sandstone. Four boreholes have penetrated the underlying Boda Claystone Formation to considerable depths (a few hundred meters). Two of these boreholes were drilled in 1991 to 1200 m depth to obtain information about the vertical characteristics of the claystone over most of its thickness. In 1993, a specific study program was started within the framework of the National Waste Disposal Program to further examine the Boda Claystone Formation. The following activities have been carried out under this program:

- several underground core drilled boreholes;
- an access tunnel (280 m length), about 80 m into the Boda Claystone);
- systematic sampling in the tunnel;
- geological mapping (and documentation) of the tunnel walls including the subsequent tunnel faces;
- hydrogeological boreholes, corresponding measurements, and collection of water samples;
- rock mechanics measurements during the excavation of the tunnel, and after completion;
- geophysical measurements;
- geochemical, mineralogical and geomechanical laboratory investigations in affiliated institutions; and
- laboratory testing of water samples.

So far, the investigations from this exploratory tunnel and two previous deep surface boreholes, BAT-4 and BAT-5, indicate that the Boda Claystone Formation is a highly compact rock unit of very low overall permeability ($<10^{-10}$ m/sec). Based on an understanding of the faults, fractures and their relative movements from studies of the overlying uranitun bearing sandstone, it is believed that most of the faults in the claystone are sealed and filled with calcite, barite, gypsum and clay minerals. The accumulated data suggests there are only a few widely spaced fault zones in the Boda Claystone Formation. Methods to determine the location, orientation, extent and hydrogeologic characteristics of these faults are currently being assessed.

The objective of all the above studies was a preliminary characterization of the Boda Claystone Formation as a potential host rock for a high-level radioactive waste repository. The results obtained so far confirm the geochemical and hydrogeologic suitability of the claystone for HLW disposal and favor further investigation of this claystone formation. This is particularly the case in view of the fact that there is not a wide choice in Hungary of suitable geological formations (size and quality) for a HLW repository.

12.5 GEOLOGICAL STRUCTURE OF THE AREA

The Western Mecsek Mountain Permo-Triassic inlier is bounded to the north, south and east by three left-lateral, strike-slip faults. These enclose gently eastward-plunging (~10°) folds. A broad anticline, flanked by smaller synclines, contains the detailed area of interest, and is bounded to the north by a 30° south-dipping reverse fault, and to the south by a 50° north-dipping reverse fault. Both of these faults strike east-northeast and are paralleled by lesser reverse, normal and oblique-slip faults with high intermediate to subvertical dips that are connected by splays in some cases. A further set of east-dipping normal faults strike north-northwest, perpendicular to the anticlinal axis.

The stratum of interest, the Boda Claystone Formation, is a silty claystone at least 800 m thick. This is a lacustrine deposit set within a sequence of fluvial sandstones all of which were deposited in a semi-arid climatic environment. The claystone is bounded beneath by a conglomeratic sandstone (Cserdi Formation) concordantly gradational over 100 m. It is bounded above by another conglomeratic sandstone (Kővágószölösi Formation), which contains the uranium deposits mined by Mecsekurán Ltd. This upper contact is gradational over 40 m but is discordant in places.

The Boda Claystone Formation is exposed at the surface over an area of about 20 km^2 near the village of Boda. In order to evaluate this formation, it will be necessary to study the entire unit, down dip from the surface outcrop towards Shaft IV (transportation and ventilation)

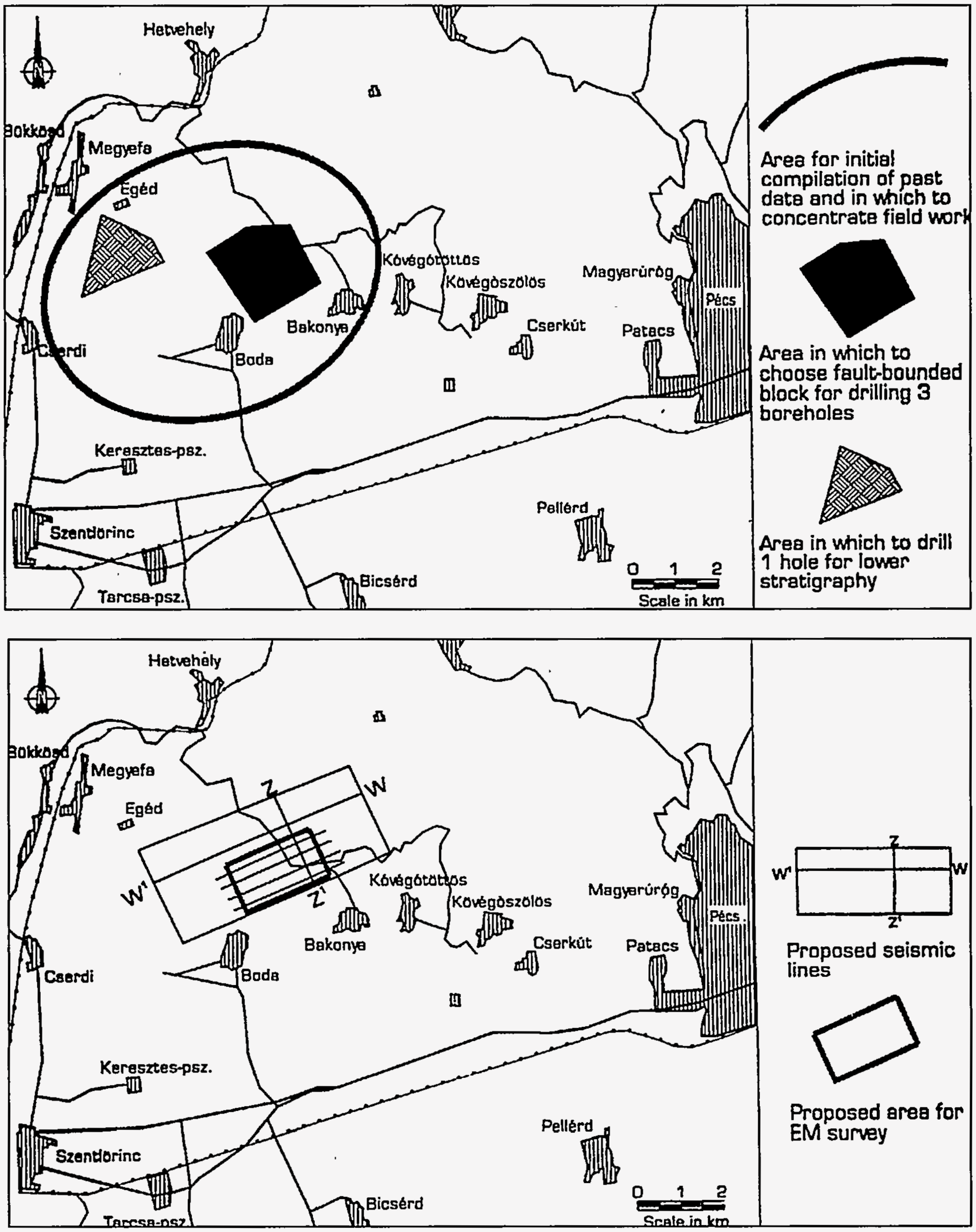


Figure 12.1. Proposed surface geological and geophysical investigations.

and Shaft V (transportation). This will define a candidate area of approximately 40 to 50 square kilometers, as shown in Figure 12.1. The tentative regional study area is marked on Figure 12.2 by boundary IJKL. It is estimated to contain about 40 cubic kilometers of Boda Claystone Formation with an average thickness of 800 m, in which exploration can be carried out for the selection of possible disposal sites. The northern boundary could be extended further to I'J', if necessary.

Being a lacustrine deposit, the Boda Claystone Formation, probably varies lithologically over much larger distances laterally than vertically. It contains several stratigraphic members in the vertical, stratigraphic

Figure 12.2. Geological map showing proposed study area.

section, without obvious boundaries but with slightly different properties. In general, the chemical composition is quite uniform throughout stratigraphically; it is composed of quartz and feldspar with a high clay content and a significant amount of fine grained hematite. The claystone has a higher quartz content in the upper part of the formation, and the matrix contains up to 10% primary dolomite in layers 1-10 cm thick. The claystone is generally oxidized but a few unoxidized layers are evident in the geologic logs of some boreholes drilled from the surface. These layers can be at least up to 20 m thick.

Knowledge of the location, extent and hydrogeologic properties of fault zones and fractures within the Boda Claystone Formation is of critical importance in selecting a suitable location for a high-level waste repository. Based on geologic mapping of the overlying sandstone in the uranium mine, it is clear from a WSW-ENE cross-section that the 700 to 900 m thick claystone stratum may be offset by a number of WSW-ENE trending fracture zones. This claystone may also be affected by north-south trending subvertical faults. From recent mapping in the "Alpha" exploratory tunnel at the 1100 m depth in the mine, two dominant sets of mesoscopic fractures have been observed in the Boda Claystone Formation. These fractures are filled with calcite and clay minerals, and are apparently sealed to groundwater flow. It will be essential to develop a much more detailed understanding of the lithological, hydrogeological, geophysical, geochemical and geomechanical conditions of this claystone and adjacent formations and crosscutting faults to develop performance assessment models in order to evaluate different areas of the Boda Claystone Formation for a high-level waste repository.

12.6 CHARACTERIZATION PROGRAM OUTLINE

The region of the Boda Claystone Formation that has been identified as a potential siting area will require a comprehensive characterization program to select the preferred disposal site. The existence of an access tunnel from the uranimn mine into the claystone at 1100 m, provides an opportunity to characterize some potentially important vertical structures that could act as groundwater pathways through the claystone. Thus, the characterization program for this particular area in the Boda Claystone differs from the program that would be developed for a site or formation where there is no existing underground access.

The characterization activities are part of a long-term program that could take 7 to 15 years to complete before a final disposal site in the Boda Claystone is approved. However, there is a need to determine whether or not a long-term program should be initiated in the Boda Claystone. The objective of this short-term program is to consolidate the information that has been gathered during 40 years of mining related activities in this region, collect new information from selected target areas and develop a comprehensive geotechnical model for the region.

Very slow groundwater movement or diffusion within pores and fractures in the Boda Claystone Formation, surrounding the site eventually chosen for the repository, is expected to provide an effective barrier to the release and migration of repository contaminants. Adsorption on the clays in the rock matrix and fracture fillings is also expected to be a major factor in retarding the contaminants. Thus, a thorough knowledge of the groundwater flow and diffusion paths through the claystone and adjacent rock formations is required to determine the likely pathways for radionuclide migration from potentially suitable repository locations to the human environment.

The main problem in characterizing the candidate area is to choose a location for the repository such that the hydrogeologic and geochemical conditions will delay and impede the release and migration of repository contaminants to the accessible human environment. This will involve both surface and underground evaluations of the Boda Claystone Formation and the overlying and underlying sandstone formations in the candidate area.

A major emphasis in the site characterization program would be on developing an understanding of the physical and chemical conditions of the groundwater pathways in the claystone and determining how these conditions interact with the fluid flow conditions in the overlying and underlying rock formations. Another emphasis would be on determining any future change or disruptions that could affect these flow conditions. Still another emphasis would be on determining how any future changes or disruptions, during the construction or operational stages of the repository or during the time frame of concern for long term assessments of performance, could affect groundwater movement in the Boda Claystone Formation.

Because this claystone has a very low primary permeability, yet is situated in a geologic setting that has been faulted and fractured, it will be necessary to determine the geometry and hydraulic properties of the fracturing at different scales within the formation to develop an understanding of the groundwater flow conditions. The groundwater regime in the overlying Permian sandstone has been dramatically affected by the uranium mining activity, and therefore, it will differ from original conditions. The disturbed hydrogeological regime in the overlying Permian sandstone may have altered the groundwater conditions in the Boda Claystone, and these effects will also need to be evaluated.

The data gathered from these activities and data already collected by Mecsek Ore Mining Company, and other Hungarian institutions can be used to select a preferred site for a HLW repository within the potential siting area. There are two possible alternatives that would affect the characterization program. They are:

- the preferred repository site is close enough to the uranium mine so that the site can be accessed from the mine; or
- the preferred site is located such that a new access from the surface would be necessary or preferred.

If the preferred repository site is chosen near the location of the uranium mine in the overlying sandstone so as to be accessible from the mine, the local characterization program would include some surface boreholes to provide information immediately around the repository. However, the majority of the characterization program would probably be conducted underground from currently existing and new access tunnels.

If the preferred repository site is located away from the uranium mine where new access from the surface is required or preferred, the initial characterization will be mainly from the surface into the undisturbed portion of the Boda Claystone Formation and will progress logically to underground characterization activities as new access to the underground is constructed.

Under normal circumstances, a characterization program to select a preferred site for a HLW repository would initially be surface based, followed by an underground evaluation program at the preferred site using exploratory shafts and tunnels. This is the approach recommended by Davison et al., for the Canadian nuclear fuel waste disposal concept. In the case of the Boda Claystone Formation, the underground environment has already been accessed by an underground tunnel at 1100 m depth from the adjacent uranium mine, thus providing the opportunity to conduct further underground characterization activities, if there are both cost and technical advantages to doing so.

Because the area presently under consideration as a nuclear fuel waste disposal site is relatively large (40 km^2), both surface-based and underground characterization programs are recommended. One of the normal advantages of a surface-based characterization program is that the underground environment is relatively undisturbed prior to excavation. This allows background measurements of the undisturbed conditions at the site to be obtained from a network of surface-based characterization boreholes, and allows the construction of a detailed model of the groundwater regime at the site. Predictions of drawdown resulting from shaft sinking and the excavation of exploratory tunnels can be made and compared to actual measurements to assess the accuracy of the hydrogeological model.

For the characterization of the Boda Claystone Formation, the fact that many of the potential faults extending down from the overlying sandstone formation are sub-vertical means that they are better accessed and instrumented using sub-horizontal boreholes that are easily drilled from the underground. However, there are significant operational problems associated with conducting characterization activities from the underground. Firstly, there may be limitations on the drilling of long exploratory boreholes underground due to technical factors. The drills presently used underground at the uranium mine are apparently limited to drilling boreholes to a maximum length of 300 m. Suitable equipment to drill longer, and perhaps larger diameter boreholes would need to be acquired. In addition, the ambient rock temperature at the depth of the present access tunnel into the Boda Claystone Formation is about 45° C. If this exploratory tunnel is advanced further into the claystone, the distance to the closest shaft will increase, and with it the problem of cooling and ventilating the working areas.

The present laboratory tests and measurements from the exploratory access tunnel were finished by the end of 1994. Based on the encouraging results of these characterization activities, further investigation of the Boda Claystone Formation as a host formation for HLW disposal was recommended; there is not an abundant choice of suitable geological formations (size and quality) in Hungary for siting and for economic reasons.

The activities recommended for characterizing the Boda Claystone Formation, both surface-based and underground, have been organized according to discipline and/or activity. For both approaches these include: geological mapping, geophysical surveys, exploration drilling, hydrogeological monitoring and testing, geochemical and hydrogeochemical studies, *in situ* stress determinations, site modeling and model validation, laboratory testing and analyses, and seismic risk analyses.

In addition, it is recommended that full-scale, *in situ* tests be conducted underground in representative geological conditions. Such tests could include: radioactive migration testing, excavation response studies, thermal studies and tests, thermal studies on rock behavior, testing of mining methods related to minimizing the disturbed zone, and ground support methods in the Boda Claystone Formation.

12.7 SHORT-TERM CHARACTERIZATION PROGRAM

A short-term characterization program is proposed as part of the activities being carried out to investigate the suitability of the Boda Claystone Formation as a host rock for a high-level nuclear waste repository. The objective of the short-term study is to gather, analyze and interpret existing and new information on this formation in order to decide whether to begin a long-term investigation of the claystone as a suitable high-level, radioactive waste disposal medium.

The current situation regarding geoscience investigations in the Boda Claystone Formation is as follows. Data from previous investigations carried out during the development of the mine, some going back as far as 40 years, are available. There are also several investigations in progress at the present, and the necessity of initiating some entirely new investigations or repeating earlier surveys, where the results were not satisfactory in the present context, has been recognized. Analysis and interpretation of all of the above described data will be required in order to make a decision on a long-term characterization program. To assist in the compilation of these data, a computerized database will have to be established, so that data are available, on a systematic basis, for compilation, interpretation and modeling.

The field component of the proposed short-term program will consist of surface as well as underground activities. The latter are divided into two phases; the first phase of the underground activities will not include further excavation, whereas the second phase will be based on additional excavation.

There are certain time constraints on the short-term program, due to the governmental decision to close the uranium mine by 1997. All field activities, both surface and underground, must be completed in a two-year period, commencing in May 1995. Analysis and interpretation of field data must be completed within a reasonable time period after March 1997.

The short-term characterization program will concentrate on confirming the important processes controlling groundwater flow and possible radionuclide, transport in the Boda Claystone Formation. Particular attention will be paid to developing an understanding of the occurrence and geotechnical properties of tectonic zones, or fracture zones, within the claystone. Knowledge of the location, extent, hydrogeological properties, geochemical properties and geomechanical properties of tectonic zones and fracture zones within the Boda Claystone in the candidate siting area is needed to develop models of the groundwater flow pathways within the Boda Claystone Formation in order to conduct assessments of the long-term safety and performance of a repository in the claystone.

Investigations carried out over the past 40 years during the development of the uranium mine, indicate that the Permian sandstone overlying the Boda Claystone Formation is cut by a series of inclined fracture zones. Based on geological mapping, these fracture zones may be spaced as close as 50 to 200 m. Evidence from the "Alpha" tunnel, at the 1100 m level of the mine indicates that these fracture zones are water bearing but that the blocks of Boda claystone bounded by these fracture zones are relatively impermeable. There is no information on the occurrence, distribution or hydrogeological and geochemical characteristics of these fracture zones within the Boda Claystone Formation. The short term characterization program involves performing some surface-based characterization studies (including deep borehole drilling) near the outcrop area of the claystone and by performing some underground characterization studies in the existing exploratory tunnel into this formation from the 1100 m level of the uranium mine.

At present, little is known of the faults and fracture network in the Boda Claystone Formation at the depths proposed for the repository. This information can best be obtained by borehole drilling, combined with geophysical surveys and with some detailed geological mapping of fault subcrops if access is available. Also, hydrogeological investigations and hydrogeochemical sampling in the boreholes will be very important components of subsurface characterization. Analysis and collation of existing data through a database will also be very useful.

Because of the time constraint, only a largely conceptual model of the controls on groundwater flow through the Boda Claystone, as opposed to a partly idealized deterministic model, can be developed. Therefore, the surface investigations are to be concentrated in a few areas (at least two) from which a good understanding of the principal factors controlling the flow of groundwater can be obtained.

It is suggested that the surface geological investigations (surface mapping) be confined to the same area as the proposed geophysical surveys. The two principal objectives of surface mapping are to:

1. determine the location and conduct fault-rock characterization for the subsurface projection of faults in the Boda Claystone, especially those that are potential drilling targets. This can be achieved by detailed mapping, from outcrops or trenches, of topography, mesoscopic fractures, rock alterations and fracture fillings. This work will be concentrated in the area in which a fault-bounded block is likely to be chosen as a drilling target.
2. determine the general character and history of ductile, brittle deformation of the Boda Claystone, and decide whether lithologic variation is likely to be important. For example, the bedding attitude data in the underground tunnel into the Boda Claystone from the 1100 m level of the mine suggest crossfolding in the claystone with a NW to NNW plunge. Such zones of folding may be centers for more concentrated mesoscopic fracturing.

Drilling and geoscientific and geotechnical characterization of four deep boreholes from the surface is proposed. Three boreholes are to be drilled to investigate conditions and to characterize the bounding faults within two adjacent fault-bounded blocks within a 3-4 km radius to the northeast of the village of Boda. Borehole depths would depend on the actual location chosen, but two of them should be 500-700 m deep. The third should be at least 1300 m deep and penetrate the sandstone footwall. The fourth borehole is to be drilled approximately two km northwest of Boda within the outcrop of the Boda Claystone Formation. This hole is also expected to be about 1300 m in depth to obtain hydrogeologic information in an area expected to have sparse faulting. This borehole should penetrate well into the footwall and be used to characterize the lower members of the Boda Claystone Formation, geoscientifically and geotechnically.

12.8 CONCLUSIONS AND PROSPECTS

In 1993, the decision was taken to develop a relatively inexpensive access from the existing mine to study the adjacent formations. This involved developing and servicing an exploratory access tunnel from the uranium mine into the Boda Claystone Formation. This exploratory access was completed in 1994. The tunnel has been used to conduct a preliminary research program to study the *in situ* characteristics and properties of the claystone. These data have contributed to assessing the potential suitability of the Boda Claystone for high-level waste disposal in terms of safety assessment and repository design. The results from these preliminary studies have continued to confirm the geochemical, geomechanical and hydrogeologic suitability of the Boda Claystone as a host media for high-level waste disposal in Hungary.

As the Boda Claystone Formation has been identified as a potential high-level waste disposal site, experts are now developing a thorough program to assess its suitability. This will require that sufficient data be gathered on the characteristics of the claystone to select appropriate location(s) for a repository and to complete a safety assessment for a repository at each location. An extensive database of geologic formations exists for the area of the uranium mine, both from the previous surface-based exploration programs as well as from the underground characterization program. Much of information is relevant to understanding conditions in the Boda Claystone beneath the uranium bearing Permian sandstone. The structural information on jointing and fracturing is particularly relevant to the identification of suitable locations for a high level waste disposal repository.

The most probable way for radionuclides, that are sealed in a deep geological repository to reach humans and the environment is by transport in groundwaters through the pores and cracks in the rock surrounding the repository. Therefore, one major requirement in characterizing possible repository sites in the Boda Claystone Formation is to quantify the important processes governing the transport and absorption of radionuclides within the groundwater systems in the rock mass as well as the engineered barriers used in the repository. Groundwater movement in rocks such as the Boda Claystone is mainly controlled by the presence or absence of fractures, the permeability and interconnectivity of these fractures, the permeability and porosity of the unfractured rock, and groundwater pressure gradients. The chemistry of the groundwater, the rock matrix, and minerals within the fractures also govern the potential transport of radionuclides within groundwater. Therefore, the presence of open fractures (joints and bedding planes), fracture zones and processes that can change their hydraulic or chemical properties, must be understood for repository siting and design.

Two underground facilities are likely to be necessary for the characterization of a site and the design of a repository in the Boda Claystone Formation. The first facility is the Underground Characterization and Test Facility (UCTF) that is being started with the construction of the Access Tunnel from the Mecsekurán uranium mine into the claystone. It will be used to provide information on the suitability of the claystone as a repository medium as well as preliminary repository design information, and to train staff, develop methods and study design and safety issues. Because it is located near the uranium mine and the contact between the sandstone and the claystone, it is likely to be in a disturbed environment.

The second facility is a repository characterization facility (RCF), to be located at the preferred repository site, which would be constructed late in the site characterization stage. It would provide access to the repository rock volume for final assessment of the site suitability, and for commissioning and longer-term coupled interaction tests on repository systems and components. It would be incorporated into the repository design so that its excavations would become part of the repository and would not interfere with the repository operation.

The UCTF will be located in a section of claystone that likely has been influenced by the mine construction and operation. In particular, the groundwater pressures, flows and chemistry in the sandstone, and perhaps the claystone, are likely to be affected by the presence of the mine. As there has not been a long-term hydrogeological monitoring program in the sandstone and claystone near the mine, the original groundwater conditions and the magnitude and areal extent of the disturbance caused by mining activities over time are not known.

Without this information, studies and demonstrations that require regional groundwater conditions as a step in planning or in performance and safety related analyses may not be possible with the limited data gathered from the UCTF. These studies will have to planned as part of RCF activities at a preferred repository site where these data can be collected. However, significant groundwater studies can still be done in the UCTF to:

- develop and demonstrate the equipment, instrumentation and procedures for drilling and monitoring groundwater conditions in boreholes;
- install monitoring systems in new and existing boreholes to study the hydraulic connections in fractured rock; and
- observe the pressure and chemistry changes that occur when new boreholes and excavations are done.

These are valuable and necessary studies in preparing for the characterization of a potential repository site, and for the environmental and safety assessments. These studies will also be used to select the methodologies that should be applied in the characterization and assessment studies that will be conducted at the preferred repository site.

Also, it is our understanding that the mine operations have been confined to the sandstone formation. This may make it possible to assess the impact of a large "drain" (i.e.,. the mine in the sandstone and the UCTF in the claystone) on the pore water pressures within the Boda Claystone Formation. If it can be demonstrated that the pore pressures in this claystone have been only slightly affected by the presence of the mine and the development of the UCTF, this information can be used to demonstrate the large-scale low permeability of the claystone, an attractive characteristic for waste disposal. This type of *in situ* information can only be obtained by monitoring the response of the groundwater system to construction of underground excavations such as the access tunnel and the UCTF.

The effects of the mine excavations on the mechanical conditions in the claystone around the UCTF will probably not significantly influence the studies and demonstrations that may be planned for the facility. However, the proximity of the UCTF to the contact between the sandstone and the claystone may have to be considered in analyzing the data from UCTF studies and in extending the results to a potential repository site elsewhere in the claystone.

The second underground facility, the repository characterization facility (RCF), would be constructed at the preferred repository site during the later stages of repository site characterization to conduct tests: (a) to confirm the suitability of the site for disposal; (b) complete the repository design; and (c) refine and test repository systems and components. The RCF design would be integrated into the repository. As the repository site will likely be several kilometers away from the uranium mine and away from any other underground excavations, it should have a relatively undisturbed groundwater environment. In the site characterization program at the potential repository site, the regional characterization and the long-term hydrogeological monitoring would be done prior to any underground excavation so the baseline hydrogeological and chemical conditions would be known. The changes in these conditions caused by additional borehole drilling, and by the excavation and testing in the RCF would be known. The changes in these conditions caused by additional borehole drilling, and by the excavation and testing in the RCF would be measured and could be used to develop and test computer models that will be used to predict the performance of the groundwater system.

REFERENCES

Buday, G., Recent status of spent fuel storage in Hungary and outlook to the future, IAEA AGM, Vienna, April 15-18, 1992.

Buday, G., and G. Ferenczi, Status of the nuclear fuel cycle back-end strategies, IAEA TGM, Vienna, June 1-4, 1993.

Ormai, P., L. Maróthy, and K. Bérci, Hungarian policy on the back-end of the fuel cycle, VVER Nuclear Waste Management Workshop 92, Toronto, Canada,1992.

Vigassy, J., I. Czoch, and P. Ormai, Hungarian experience with the National Project for Radwaste Management, Symposium on Waste Management, Tucson, USA, 1994.

A recommended program for the characterization of the Boda Claystone Formation as a potential site for the safe disposal of high-level radioactive wastes, Report by AECL Research, 1995.

Design requirements for the construction and operation of an underground characterization and test facility in the Boda Claystone Formation, Report by AECL Research, 1993.

CHAPTER 13

STATUS OF SITING AND HOST ROCK CHARACTERIZATION PROGRAMME FOR A GEOLOGICAL REPOSITORY IN INDIA

R.K.Mathur, P.K.Narayan and A.N. Prasad

Bhabha Atomic Research Centre, Bombay-400085, India

13.1 INTRODUCTION

The Indian programme in search of suitable sites for location of a deep geological repository for disposal of high level vitrified waste has been in progress for the last few years. The whole country has been screened, based on well identified criteria, for suitable host rock formations in tectonically stable areas. The programme is being pursued in a phased manner in stages, to narrow down the choice from larger areas to a few candidate sites of specific size. In parallel, a study is underway to directly evaluate and characterize the host rock lying within the exclusion zone of a nuclear power plant for locating a possible waste repository.

The main host rock under consideration is a plutonic granitic formation available in tectonically stable areas and having homogeneous and uniform geological, structural, physico-chemical and hydrogeological characteristics with a favorable socioeconomic environment.

Out of thousands of square kilometers of granitic areas screened, the choice has been narrowed down to a few granitic zones of 100 - 150 sq. km. Two such zones have been investigated in detail to further demarcate the most suitable sub-zones. Micro level investigations are to be taken up in the sub-zones to assess the possibility of finding the repository candidate sites.

In one of the sites, geological, hydrogeological, geophysical (preliminary), environmental and socioeconomic surveys have been completed, whereas in the other, deep drilling down to a depth of 620 metres is in progress. Simultaneously, laboratory investigations to evaluate mineralogical, petrographical, micro-structural, thermal, mechanical, physical and chemical properties of the rockmass are also in progress. Modeling studies for joint fracture characterizations, ground water flow and radionuclide migration, and stress behavior in a conceptual repository have been taken up. Geophysical surveys, bore hole logging and *in-situ* stress measurement are underway.

13.2 REPOSITORY SITE SELECTION PROGRAMME

The programme is aimed at selecting one or more geological repository sites and characterizing them for final disposal of immobilized high level radioactive waste, through various stages of investigations comprising field and laboratory studies. To carry out the multi-disciplinary investigations, a number of national expert organizations/agencies have been involved to address specific issues.

13.2.1 Major Site Selection Criteria

The major criteria on which the selection of a candidate repository site depends are:

- Tectonic stability of the area;
- Three dimensional homogeneity, large extent and massiveness of the host rock mass;
- Suitable hydrological and hydrogeological environment;
- Favorable thermal, thermomechanical and geochemical properties of host rock; and
- Favorable socioeconomic factors.

13.2.2 Stages of Site Selection

The approach followed for site selection is to narrow down the choice of the area with an increasing level of confidence. This is planned to be achieved in different stages, reducing the size of the area to smaller entities at every stage. The following main stages are considered:

Stage I. Collection of all available data from various sources and their interpolation to evaluate specific attributes for delineating promising zones. Such data have already been generated and a few zones have been identified for further investigations.

Stage II. Mainly semi-detailed studies including data generation through field surveys, geological mapping, hydrological investigations, collection of soil/rock/ water samples and their analysis. Based on the data generated during these investigations, two zones have been identified for further studies.

Stage III. Extensive field surveys, detailed geological and structural mapping, subsurface investigations and intensive analysis and interpretation of all parameters. Detailed geological and structural mapping of the potential zones has already been initiated. Subsurface investigations have also been planned in this stage.

Stage IV. Micro level studies, subsurface characterization with the help of geophysical investigations and ground water flow studies.

Stage V. Finalization of site for pilot repository from one of the selected sites. Further detailed investigations by conducting *in-situ* experiments.

Stage VI. Final stage involving actual design and construction of a full fledged repository.

13.2.3 Evaluation of Zones and Methodology

Based on the criteria developed, a number of attributes have been identified for data acquisition, collation and interpretation. An attribute is a factor or a parameter having varying degrees of influence on the geological, mechanical, hydrological, thermal and radiological integrity of the proposed repository. Each attribute has been allotted a weighting factor depending upon its relative importance at each stage of repository siting. In Stage I, 20 attributes as listed in Table 13.1 were thoroughly examined. Each attribute was allotted a maximum score point of 10 and a minimum of 0. These attributes have been organized and grouped based upon their relative merits in different stages of the programme.

Initially geological, structural, tectonic, geomorphological and socioeconomic data were collected and represented on 1:25,000 scale for further evaluation. All the granitic areas were then divided into grids of 20 x 20 km or 10 x 10 km. Each unit was taken as a candidate unit for matrix analysis. The units scoring maximum points were considered as promising zones for further evaluation. Based on the product of score points for each attribute and the corresponding weighting, a relative grading was determined using the following equation:

Table 13.1. List of attributes considered in Stage 1.

No.	Attribute
1.	Lithological formation
2.	Seismicity
3.	Distance form stuctural discontinuities
4.	Distance from surface water bodies, viz. dams/rivers/lakes, etc.
5.	Ground water level
6.	Rainfall
7.	Surface water runoff
8.	Population
9.	Distance from economic mineral occurrences and mining activities
10.	Distance from industrial/archeological/tourist/ religious spots
11.	Floods
12.	Soil cover and weathering pattern
13.	Vegetation cover
14.	Accessibility of the area
15.	Intensity of intrusives, veinlets, etc.
16.	Joint patterns, fracture pattern, etc.
17.	Topography
18.	Dip of formation/foliation
19.	Homogeneity of rock mass
20.	Political awareness

$$GI = \Sigma\ Wi\ x\ Pi$$

where: Wi = weighting factor of attribute, Pi = Score points against an attribute, and GI = grade index for suitability.

Until now, this methodology has been adopted in Stage I and has enabled an identification of two favorable zones of 100 to 150 sq. km for detailed investigations in Stage II.

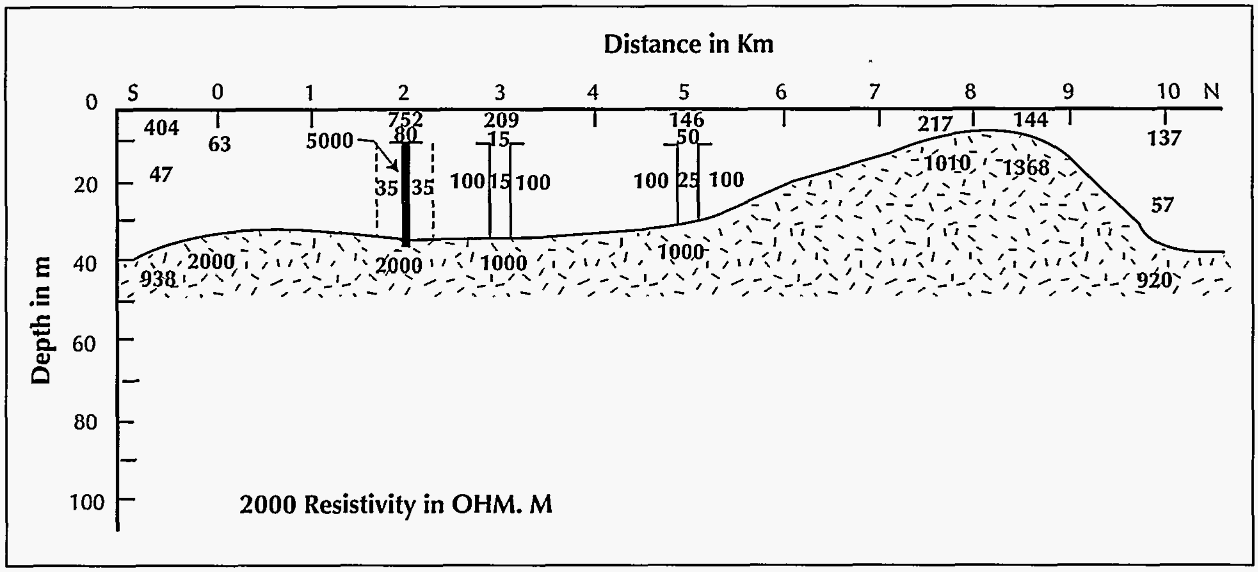


Figure 13.1. A resistivity section along the main N-S traverse P1, based on joint DCR and HLEM 1-D inversion and limited 3-D modeling.

In the second stage, demarcation of two zones of 25 to 30 km^2 has been achieved. In the third phase, further narrowing down of these zones to those of four sq. km each will be considered. They will then be treated as test or candidate sites.

The methodology adopted in this programme has been found to be most suitable. Subsurface investigations have now been planned for further characterization of the granitic rockmass. The zones so far identified largely satisfy the conditions of compositional and structural homogeneity, massiveness and a suitable hydrogeological set-up. The rainfall in these zones is scanty, population density very low, and vegetation cover almost negligible.

13.3 Repository Site Characterization Programme

While characterizing a particular rock formation for its structural and compositional homogeneity, a thorough assessment of its geological, structural, hydrogeological, geophysical and petrographic characteristics is essential. In addition to the above investigations, it is also required to study various thermal and mechanical properties of the rockmass so as to understand its behavior at elevated pressures and temperatures.

13.3.1 Geophysical Characterization

Geophysical surveys involving electrical methods were carried out at one of the promising zones to test the suitability of various methods to evaluate the homogeneity of the granitic rock mass under investigation and detection of fracture zones, intrusive rocks etc. The observations were recorded over a path length of 12 km at an interval of 100 m. The line was so selected as to almost bisect the area. The following methods were employed to achieve the objective:

1. Direct Current Resistivity (DCR) method to obtain information at greater depths;
2. Horizontal Loop Electro-Magnetic (HLEM) method to probe shallow depths; and
3. Very Low Frequency (VLF) method to get near surface information.

Based on the data obtained, it has been interpreted that beneath a sandy top cover, weathered to semi-weathered granite exists between varying depths of 7 to 60 m below the surface with unweathered fresh granite below these depths. A dyke was also demarcated along the line of a survey. Figure 13.1 shows the vertical section along this line.

Besides these surveys, a seismic sounding was also carried out over selected outcrops along two short orthogonal lines using a hammer source. This experiment was conducted for studying seismic propagation characteristics of the area when there is little or no sand cover.

From the above investigations, the following possible

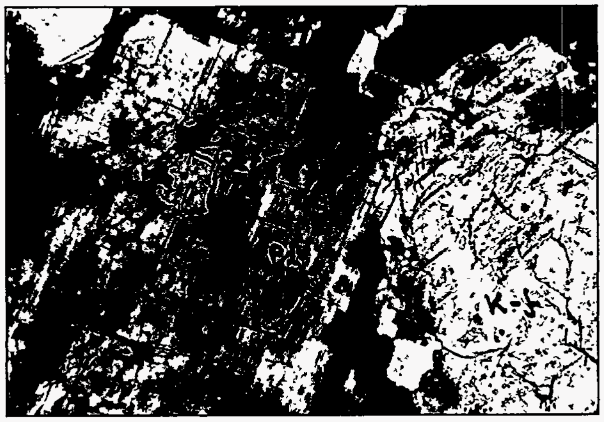


Figure 13.2. Plagioclase feldspar (P1) and K-feldspar (k-f), filled with sericite in a thin section of granite. Network of microcracks are also observed. Under crossed polars (x16).

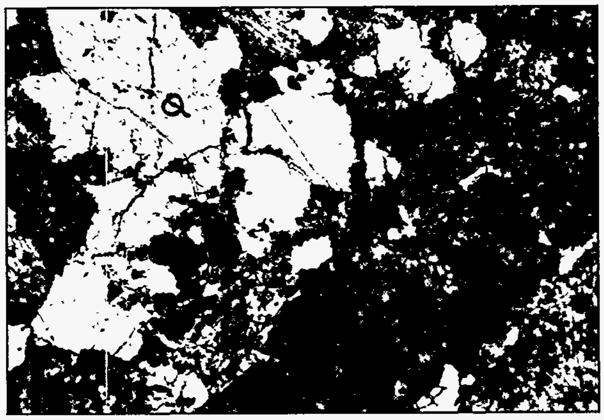


Figure 13.3. Microcracks in quartz and plagioclase (P1) in a granite thin section. Under crossed polars (x16).

subsurface conditions have been brought to light:

- Extensive cover of loose sand;
- Low resistivity near the surface indicating higher degree of weathering of the top zone;
- Highly variable surface and near surface electrical resistivity and seismic velocity; and
- Possible presence of shallow anomalous objects within deep weak zones in granite.

It may, however, be noted that these interpretations are based on a single test survey. More detailed investigations are planned in the near future, using advanced techniques like a Multi-channel Digital Data Acquisition System, which will retrieve very weak signals from greater depths.

A resistivity survey on a grid interval of 5 x 5 km or 10 x 10 km will be conducted shortly to assess the major elements of inhomogeneity in the rock mass down to a depth of 1 km.

13.3.2 Petrographic Characterization

Petrographic examination of selected samples of granite in the area under investigation was carried out to understand the microscopic features of the rocks. The following parameters were emphasized:

- Deformation and consequent stress effects on mineral grains, especially quartz;
- Presence of microfractures in the rock;
- Nature of alteration of constituent minerals; and
- Radioactivity of constituent minerals.

The salient petrographic features of granite in one of the zones are as follows:

- The rocks can be classified as porphyritic micro granites, micro diorites and porphyritic granophyres, with major quartz (30% to 45%), potash feldspar (22% to 54%) and plagioclase feldspar (12% to 28%). Accessory minerals include biotite, chlorite, epidote, apatite and opaques, mainly oxides of iron and titanium;
- Feldspars have undergone a considerable degree of weathering and have been sericitised. Biotites have been chloritised;
- In general, the overall degree of alteration of granites is moderate, as supported by weathering index data;
- Radioactive assay data for these samples indicate that the granite contains 15 to 20 ppm eU_3O_8. Solid State Nuclear Track Detection (SSNTD) studies indicate that no discrete radioactive phase is present in the samples; and
- In most samples, quartz is unstained and microcracks are not widespread.

The above observations suggest that the granite rock mass under investigation could form a suitable host rock from the petrographic point of view. Figures 13.2 and 13.3 show mineral assemblages and micro fractures in

Table 13.2. Compressive strength of heat treated granite.

No. of Samples	Thermal Treatment Temperature (°C)	Unaxial Compressive Strength (MPa)	Average Strength (MPa)	Standard Deviation
14	unheated	205, 194, 193 210, 205, 206 216, 196, 207 184, 192, 220 204, 209	202.93	9.96
08	100	226, 241, 208 215, 215, 225 209, 201	217.50	12.69
09	200	230, 231, 223 218, 206, 233 246, 224, 216	225.22	13.52
12	400	195, 201, 204 207, 215, 224 221, 198, 196 197, 195, 201	204.50	10.20
02	600	125, 142	133.50	

typical pink granite of the area.

13.3.3 Thermomechanical Characterization of Rock

The objective of carrying out mechanical studies on the rock samples is to understand the behavior of the rock mass at normal and elevated pressures and temperatures. This would help in modeling fracture/joint systems and to evaluate the stability of the repository.

The study pertains to the development of fractures and extension and enlargement of existing fractures, when subjected to heat induced stresses. These investigations were carried out with an Acoustic Emission Monitoring System and a High Temperature-High Pressure Triaxial Cell.

Salient features of the laboratory studies carried out are as follows:

- Uniaxial compressive strength of granite, heated to 200°- 245° C is higher than unheated and heated to 100°, 400° and 600° C samples (Table 13.2);
- Heat treated granite and charnockite undergo more axial strain and less lateral strain compared to unheated samples;
- Young's Modulus decreases with increasing temperature (Table 13.3);
- Higher stress is required to generate acoustic emission events in case of granite heated to 200° C;
- Triaxial compression experiment carried out at a confining pressure of 30 MPa indicates that the average strength of granite at 200° C is higher than that at 100° C and 150° C, but lower than the unheated samples (Fig. 13.4). Sample heated to 200° C undergoes more axial deformation;
- Uniaxial compressive strength decreases with increase of water content in the samples; and
- Preliminary analysis of results of uniaxial compressive tests and acoustic emission experiments on heat treated rocks (heated up to 245° C) appears to indicate that microcracks strengthen the rock material like dislocations in metals.

In-situ thermomechanical experiments were carried out

Table 13.3. Effect of temperature on Young's modulus.

Heat Treatment Temperature (°C)	Average Young's Modulus (GPa)
Unheated	74
100	72
200	71
300	67
400	62

in two underground chambers at a depth of 1000 m in a mine facility to study the behavior of host rock subjected to decay heat generated by high level vitrified radioactive wastes. The waste containers were simulated by electrical heaters of the same dimensions. Thermocouples, vibrating wire stress meters and extensometers were installed in the bore holes within and around the array of heaters to measure temperatures, stresses and expansions in the rockmass. The main results of single and multi-heater experiments have shown that:

- The observed temperature profiles match with those of predicted ones in the majority of monitoring points. A typical profile is shown in Figure 13.5;
- The observed heat induced stresses are about half the values of the predicted stresses, the maximum value being 45 MPa; and
- The extension of the rockmass was found to be negligible.

13.4 Captive Site Evaluation Programme

Under this programme, a charnockite rock formation has been identified for designing an underground facility. The proposed site is presently being evaluated to assess its suitability with respect to geology, structural features, ground water conditions, and the thermal and mechanical integrity of the rockmass.

In this connection, the proposed site has been studied by geological and structural mapping, resistivity surveys, soil profiling and physico-chemical analysis. Currently, deep drilling operations at the site are in progress. Three bore holes of more than 600 m depth have already been drilled and a few more are planned. Core samples from them are being studied for mineralogy, structural homogeneity, geochemistry, and thermomechanical properties. Further evaluation will be carried out by geophysical logging techniques in the bore holes to have a better understanding of the subsurface features. The measurements of *in-situ* stresses and permeability in the bore holes are to be undertaken shortly. Cross-hole seismic tomography is also planned. The study of cores indicates that the rock is massive without many open joints and fractures. Long, intact core lengths up to 6.0 m (Fig. 13.6) have been recovered from the bore holes. The ground water aquifer is confined to shallow depths in soil and weathered zones. The water is saline to some

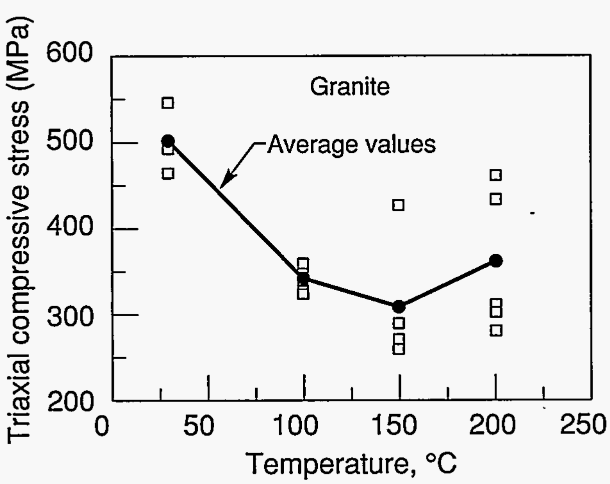


Figure 13.4. Triaxial compression test showing temperature-strength relationship.

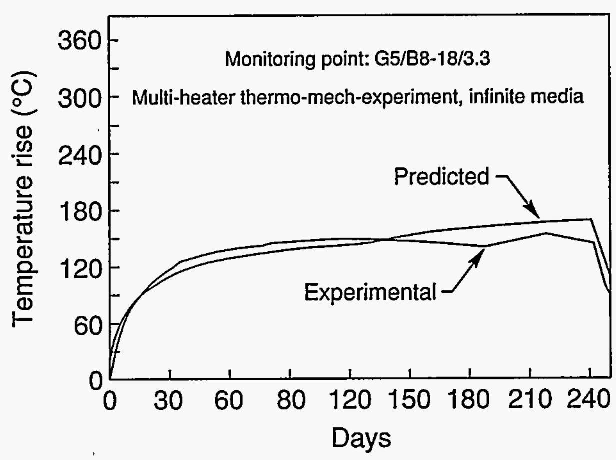


Figure 13.5. Typical profiles from *in-situ* thermomechanical experiment.

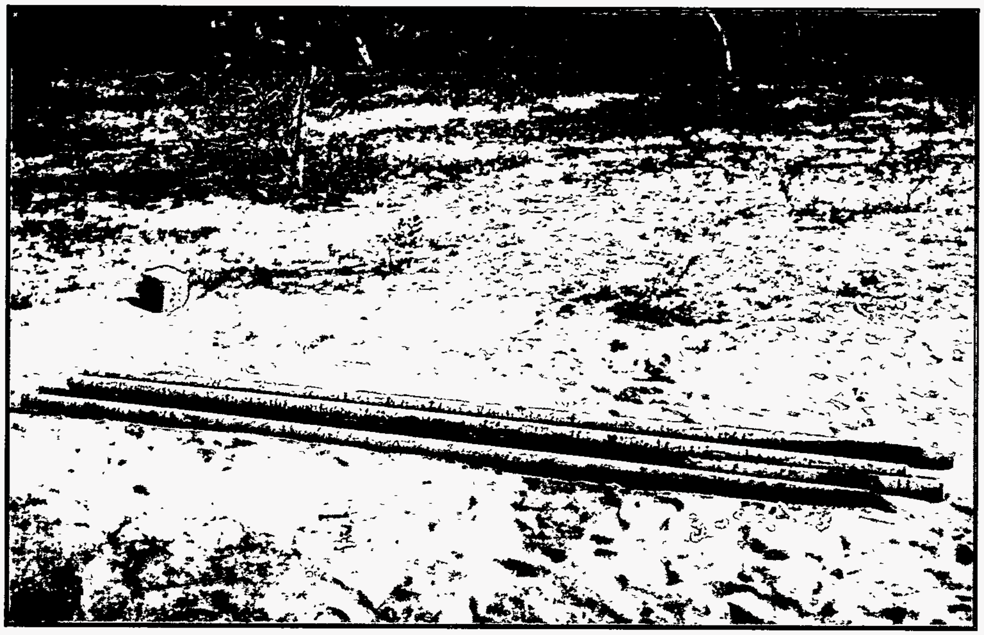


Figure 13.6. Intact long borehole core samples from charnockite formation.

extent, and the rock has good sorption properties.

13.5 CONCLUSION

The Indian programme of siting and host rock characterization for a geological repository in granite comprises selection of a site by the method of narrowing down the choice from larger areas to a specific site, on the one hand, and directly characterizing a known potential host rock formation within the captive area of a nuclear site, on the other.

CHAPTER 14

CRITICAL DATA REQUIRED TO POTENTIALLY INVESTIGATE GENTING ISLAND AS HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY SITE FACILITY IN INDONESIA

Y. U. Imardjoko, H. B. Santosa, Sunarno, N. Prabaningrum, A. Muharini, E. Wijayanti, and M. Adiartsi

Department of Nuclear Engineering, Gadjah Mada University, Ji. Grafika 2, Sekip, Yogyakarta, DIY. 55281, Indonesia

14.1 INTRODUCTION

The Indonesian archipelago is one of the regions in the world that has active volcanisms. There are 129 active volcanoes in the region. The Indonesian archipelago is developing in response to the complex interaction between the southward moving Eurasian plate, the northward moving Indian-Australian plate and the westward-moving Pacific plate (Fig.14.1). The Java trench and Timor Trough represent the major area of collision between Eurasian and Indian-Australian plates. The Sorong fault indicates the area of interaction between the Pacific and Indian-Australian plate[1].

Indonesia has been actively planning to build several NPPs in the near future, despite the concerns about the existing volcanism. The operation of these NPPs will generate waste, namely high-level radioactive wastes (HLRW). Some islands in the country have been investigated and selected as potential HLRW repository sites.

Genting island is one of these islands with a potential site for a HLRW repository site facility. A wet environment repository concept must be developed since the proposed island is an ocean-island, and the groundwater table is shallow such that the wastes will have to be emplaced in the saturated zone.

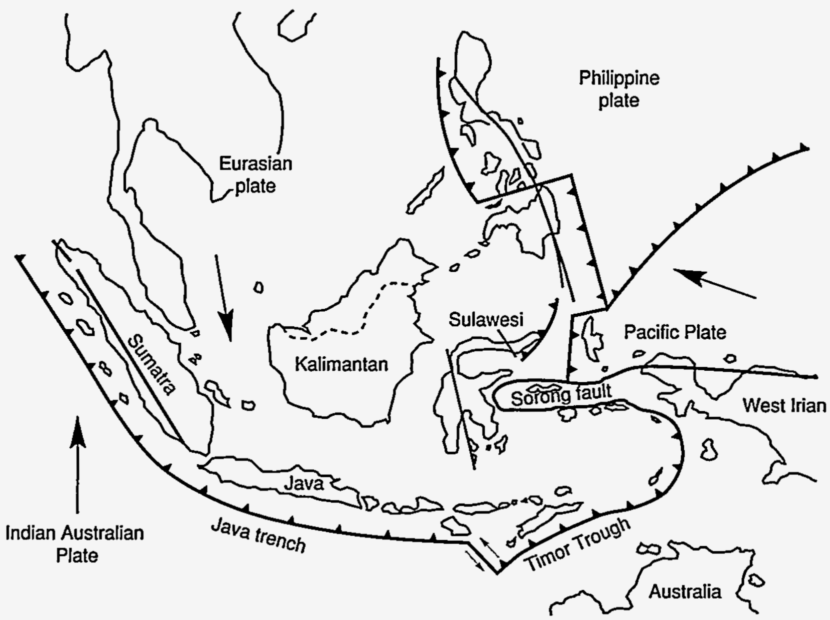


Figure 14.1. Plate boundaries in the Indonesian Archipelago.

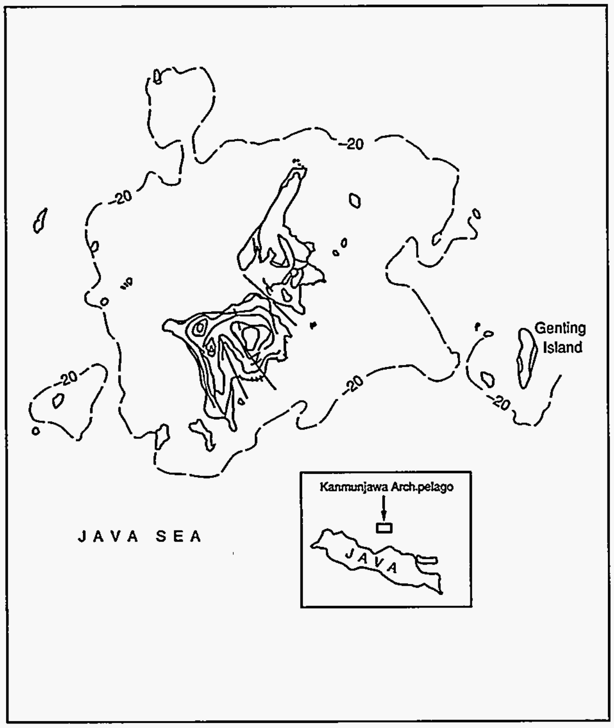


Figure 14.2. Map of Karimunjawa Archipelago showing location of Genting Island. The long-dashed line shows the location where the water depth is 20 m.

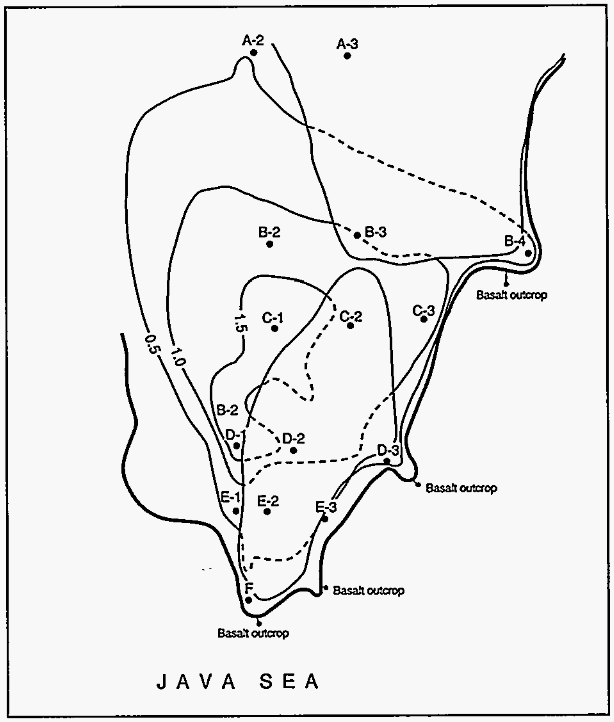


Figure 14.3. Map of groundwater levels for southern tip of Genting Island in meters above sea level. The solid lines indicate water levels that are above the land surface, and the dashed lines indicate levels that are below the land surface.

14.2 GENERAL DESCRIPTION OF THE ISLAND

Genting island is a small island situated on the north side of Java island on the Eurasian plate (Fig. 14.2)[2]. The distance from the Java trench is approximately 400 km. This island is nearly uninhabited and there is no potential economic activity. The groundwater level at Genting Island is considered shallow, and it is influenced by changes in sea level and the rate of rainfall (Fig. 14.3)[2].

14.2.1 The Lithology of the Area

The top layer (thickness ±1.5 - 3.5 m) of soil is mainly alluvium consisting of pebble, gravel, clay, coral limestone and coarse grained rocks. Below this layer is basalt (thickness ±24 - 35 m) consisting of basaltic lava or alkaline basalt, classified as a strong rock (approximate strength is 1550.36 kg/m^2 in compression)[2]. Its strength and the interlocking of fracture blocks can limit displacement along fractures. The diffusion time of radionuclides along the rock fractures can be delayed, so that it will eventually take longer for the radionuclides to reach the accessible environment (AE). The depth to groundwater is approximately 103 m. The permeability measurements of Genting Island are shown in Table 14.1.[2]

Table 14.1. Permeability measurements for Genting Island.

Coefficient of Permeability (m/s)	Type of Rocks
1.82×10^{-6}	Soil and
1.75×10^{-6}	Basalt
1.26×10^{-7}	Basalt
5.55×10^{-6}	Basalt
4.79×10^{-6}	Basalt

The water chemistry of Genting Island is such that the concentrations of Mg^{2+}, Na^{+}, and Cl^{-} are rather high in the coastal area. The content of HCO_3^- tends to increase on the southern side of the Island. The existence of

HCO_3^- in the groundwater is due to the influence of decomposed plants and swamp materials.

The southern side of the Genting Island is primarily a volcanic cone region. The highest point of this area is 40.5 m above mean sea level, and the lowest point is about 5.0 m above mean sea level.

From geotechnical investigations, the unconfined compression strength is 360.86 kg/cm^2 . The mean value of Poissons ratio is 0.31. The mean value of the rock density is 2.797 g/cm^3, and the mean value of cohesiveness is 57.87 kg/cm^2.

14.2.2 Near-Field Conditions

In the model, pH, water contact mode, and temperature are included, where pH (at the 50 m depth in an experimental borehole), varies from 7.7 to 6.8. The average pH is 7.25, which can be considered neutral. The water contact mode, in the saturated zone can be thought of as zero velocity, which indicates diffusive transport, because Genting Island is an ocean-island[3,4,5].

14.3 Design of the Repository Site

The proposed design for the HLRW repository site at the southern tip of Genting Island is divided into two areas or rings. The inner ring (called the high-temperature ring) that contains a group of waste packages with-an areal power density of approximately 100 kw/acre, which includes 75% of the waste packages. The outer ring contains a group of waste packages with an areal power density of approximately 30 kw/acre, which includes 25% of the waste packages, and represents the ambient-temperature ring[3].

14.4 Pathway Parameters

For an ocean-island repository that is sited below the groundwater table, the most important pathway for radionuclide releases is through the groundwater. The radionuclides released through the rock will eventually reach the groundwater. In the groundwater, the radionuclides will travel in a dffusive manner to the AE. Therefore, the groundwater is expected to be the primary agent affecting the performance of the Genting Island repository. In addition to being the transport mechanism for the radionuclides, the groundwater will also corrode the waste containers when it comes in contact with the containers[6]. The shallow groundwater is assumed to exist under reducing conditions. Consequently, it is also necessary to consider solubility under reducing conditions.

In regard to gaseous flow and transport, this study suggests that C-14 will not be released in any significant quantity.[3,4,5] However a more accurate analysis should be conducted. The gas flows are driven by heat and in turn affect waste package temperatures. A coupled transient model of heat transfer and gas flow employing a relatively fine grid will be required.

The ocean dilution factor plays a very important role in reducing the concentration of radionuclides released to the AE. Their concentrations become essentially negligible when this factor is incorporated in the analyses. Therefore, it is necessary to employ a more accurate model to calculate the dilution factor[7]. However, the ocean will not be considered as the source of drinking water; only the biota in the ocean should be analyzed as the potential transport pathway in future studies[5].

14.5 Summary and Conclusions

In addition to the problem of pathways for radionuclide releases, earthquakes play an important role in the repository integrity. When the rate of occurrence was selected to be $1x10^{-7}$, no effects are shown in the results[3]. But, when the rate of occurrence was taken to be $1x10^{-2}$, some significant effects were seen. Therefore, further study regarding seismic analyses of the site must be undertaken[8].

Understanding groundwater flow characteristics is essential when attempting to predict repository performance more accurately[9]. These characteristics are required, especially parameters of the directions of flow and the flow rate. Furthemore, if there are releases of radiation in the near-field environment, the possible degradation of the rocks in the buffer zone should also be further investigated[10].

References

1. Katili J.A., Magmatic affinities of volcanic rocks of Ungaran, Central Java, Journal Geologi Indonesia, The Journal of the Indonesian Association of Geologists, Volume 60, Jakarta, Indonesia, 1989.

2. Faculty of Mineral Technology, Institute of Technology - Bandung, Further Geological and Hydrogeological Investigation at Genting Island as Proposed Location for Permanent Radioactive Waste

Repository, National Atomic Energy Agency (BATAN), Jakarta, Indonesia, 1990.

3. Imardjoko Y.U., Total system performance assessment of the proposed high level radioactive waste repository at Genting Island, Karimunjawa, Indonesia, Ph.D. Dissertation, Iowa State University, Ames, IA, July, 1995.

4. Imardjoko Y.U., D.B. Bullen, and S. Yatim, Performance assessment modeling of the proposed high-level radioactive waste disposal facility at Genting Island, Karimunjawa, Indonesia, Journal Manusia dan Lingkungan, PPLH-UGM, Indonesia, December 1995.

5. Imardjoko Y.U., D.B. Bullen, and S. Yatim, Performance assessment modeling of the proposed Genting Island repository facility, Proceedings, International High Level Radioactive Waste Management Conference, ANS-ASCE, Las Vegas, pp. 172-175, NV, April, 1996.

6. EPRI, Geological disposal of nuclear waste, Electrical Power Research Institute Journal, Palo Alto, CA, May, 1982.

7. Forsberg C.W., An ocean-island geologic repository - A second - generation option for disposal of spent fuel and high - level waste, Nuclear Technology, Vol. 101, January, 1993.

8. Wallmann P.C., I. Miller, and R. Kossik, Assessment of volcanic and tectonic hazards to high level radioactive waste repositories, High Level Radioactive Waste Management - Proceedings of the Fourth Annual International Conference, Las Vegas, Nevada, Vol. 1, pp.188-195, April 26 - 30,1993, ANS, La Grange Park, IL, 1993.

9. Ahoka H., and F. Ky, Roles of fracture zones in controlling hydraulic head and groundwater flow - experience from site characterization program in Finland, High Level Radioactive Waste Management - Proceedings of the Fourth Annual International Conference, Las Vegas, Nevada, Vol. 1, pp. 431-436, April 26 - 30,1993, ANS, La Grange Park, IL, 1993.

10. Dershowitz, W.S., P.C. Walimann, T.W. Doe, and J. Geier, Discrete feature modeling at the Stripa mine in Sweden: Significance for hydrologic modeling of fractured rock masses, High Level Radioactive Waste Management - Proceedings of the Fourth Annual International Conference, Las Vegas, Nevada, Vol. 1, pp. 443-450, April 26 -30,1993, ANS, La Grange Park, IL, 1993.

CHAPTER 15

GEOLOGICAL DISPOSAL DEEP UNDERGROUND A STUDY OF THE JAPANESE GEOLOGICAL ENVIRONMENT AND ITS STABILITY

Aiji Yamato

Power Reactor and Nuclear Fuel Development Corporation,
1-9-13 Akasaka, Minato-ku,Tokyo 107 Japan

15.1 INTRODUCTION

In order to demonstrate the scientific and technological safety of geological disposal in Japan, it is important to make an accurate assessment of the geological environment and to incorporate this knowledge into the performance assessment and R & D of disposal technology based on a realistic model of this environment. At present, surveys and studies are being conducted without specification of regions or rock types.

Geoscientific knowledge to date indicates that the geological environment deep underground is characterized by generic qualities found in all regions and other qualities, which are peculiar to a specific region. For an effective assessment of the Japanese geological environment, it is important to make a systematic collection of data on specific and generic regional characteristics that are relevant to geological disposal.

Based on their origin, rocks can be divided roughly into three groups, igneous, metamorphic, and sedimentary. Within these groups, various subdivisions are categorized by mineral/chemical components, grain size and texture, etc. However, from the viewpoint of groundwater flow and mass transport, which are pertinent to the performance assessment of geological disposal, the present characteristics of rocks have a greater significance than those at the time of their formation. These characteristics include physical and chemical qualities, the hydraulic structure of rocks deep underground, and the chemical properties of rock groundwater systems, such as the extent and rate of nuclide sorption. Based on this approach, it is possible to classify the rock formations in Japan into two groups: crystalline rocks (fractured media) and sedimentary rocks (porous media). Granitic and sedimentary rocks of the Neogene are widely distributed throughout Japan and can be taken as being representative of the two groups defined above.

The Power Reactor and Nuclear Fuel Development Corporation (PNC) is promoting geological research with emphasis on present-day conditions. A new research division has been established to perform surveys and studies of the deep geological environment as a basis for research and development (R & D) programs on geological disposal.

This report outlines the R & D activities conducted so far, as well as future plans.

15.2 PURPOSE AND PROCEDURES OF RESEARCH AND DEVELOPMENT PROGRAMS

The purpose of geological research is to characterize the geological environment of Japan from the point of view of geological disposal, to construct models of geological structures and groundwater flow, to systematize available data, to make accurate and efficient assessments of the geological environment, and to develop practical technologies for analysis and evaluation purposes. The models and data obtained through such studies are applied in performance assessment and R & D programs.

Data on the flow and geochemical characteristics of groundwater, as well as on mass transport, are important in assessing the performance of the near-field and far-field in a geological disposal system. In near-field studies, it is essential to obtain accurate data on the hydraulic and geochemical characteristics of the bedrock adjacent to the engineered barrier system, including the excavation disturbed zone. For the far-field, on the other hand, data are required on the groundwater flow and mass transport characteristics of fracture and alteration zones over a wide region and on hydraulic and chemical properties at the boundary between seawater and freshwater in coastal regions.

Since data on the deep geological environment must be as precise and reliable as possible from the viewpoint of geological disposal, it is therefore necessary to develop and improve the technologies used in surveys and measurements to ensure more efficient and detailed data acquisition. Equipment is being developed that will allow surveys of bedrock with very low permeability or under the high pressure and temperature conditions prevailing deep underground in order to advance studies of hydraulic and geochemical characteristics. At the same time, attention is being given to methods which are disturbance-free, i.e. they do not cause damage or upset the natural condition of the rock. For this purpose, efforts are being directed toward improving techniques of physical and drilling surveys as well as integrating various survey techniques.

A given geological environment is considered stable for the purpose of geological disposal if the formation, selected as being most appropriate, can maintain its required role for safe disposal despite the potential for changes in the environment. In order to assess the stability of a geological formation, it is necessary to ascertain potential changes in the environment brought about by various phenomena, as well as the extent of these changes. Predictive studies require analysis of data related to the occurrence and regularity of natural phenomena (extent, region, regularity, mechanism of occurrence, etc.) and identification of a pattern of regularity, if any.

Studies on the geological environment include compiling accumulated data and the most recent findings in related fields of science and engineering and applying the results of geological R & D at the Tono and Kamaishi mines. Cooperative studies with other countries advanced in the field of geological disposal also contribute to establishing investigation techniques and procedures for performance assessment.

15.3 CHARACTERISTICS OF GEOLOGICAL ENVIRONMENT AND CURRENT STATE OF KNOWLEDGE

Deep geological formations are generally characterized by extremely slow groundwater flow and a reducing chemical environment of neutral to slightly alkaline nature. As a result, it is unlikely that radionuclides within the waste will be significantly leached out; even if the waste matrix does dissolve, the likelihood is that the escaping nuclides will either be sorbed onto clay minerals in the adjacent bedrock and fractures or will be precipitated. It is expected, therefore, that the migration of radionuclides will be even slower than the rate of groundwater flow.

Tests conducted on sedimentary rocks in the Tono region of Gifu Prefecture indicated the hydraulic conductivity to be approximately 10^{-8} m/s to 10^{-10} m/s and the oxidation-reduction potential to be low at -300 mV for groundwater at 160 m depth. In the case of the Tono uranium deposit, one characteristic of the geological environment which is evident is that no major migration of uranium has occurred in the past 10^5 years.

The deep geosphere also has the characteristic, compared to the ground surface, of not being readily affected by natural phenomena such as earthquakes, glaciation, weathering and erosion, or by human activities.

Earthquake observation in the gallery of the Kamaishi Mine indicated that the ground acceleration rate measured several hundred meters underground was approximately half that measured at the ground surface. Long-term observation of the pore pressure and chemical properties of groundwater has revealed no major change so far. Temporary changes are recorded at the time of an earthquake, but these are within the range of seasonal fluctuations (Shimizu, et. al., in press).

One of the natural phenomena considered to have a potential influence on the stability of the geological environment is the fault activity assumed to have occurred during the Quaternary. A survey of fault distributions indicates that there is a wide region without any faulting and, even within regions where numerous faults are found, there are blocks of rock where no faults exist. Igneous activity occurring in the Japanese archipelago is likely to be related to the location and depth of plate subduction in the vicinity, but there has been no major change in the past 12 million years. Periods of glaciation and sea-level changes are global phenomena which have been repeating in cycles of approximately 10^5 years for the past 7×10^5 years. An accurate understanding of regional characteristics, regularities and cycles in natural phenomena, allows the stability of the geological environment to be assessed reliably.

15.4 PRESENT RESEARCH AND DEVELOPMENT

Of the geological research and development currently underway, a report is presented here on the present studies of geological formations and on R & D procedures relating to assessing long-term safety.

15.4.1 Investigations Conducted at and Around the Tono Mine

The Tono Mine is a uranium mine situated in the Tono region of Gifu Prefecture. The region around the Tono Mine is formed basically of granite, covered with Neogene sedimentary rock (Fig. 15.1). In this region, an enormous amount of geological information is being accumulated through uranium prospecting and academic research. The shaft and gallery leading to the mine allow access to sedimentary rocks, including uranium deposits, over one hundred meters underground. Surveys conducted in this region include the hydrology and geochemistry of groundwater, mass transport by groundwater and the effect of excavating galleries on the geological environment (Yusa, et. al., 1992).

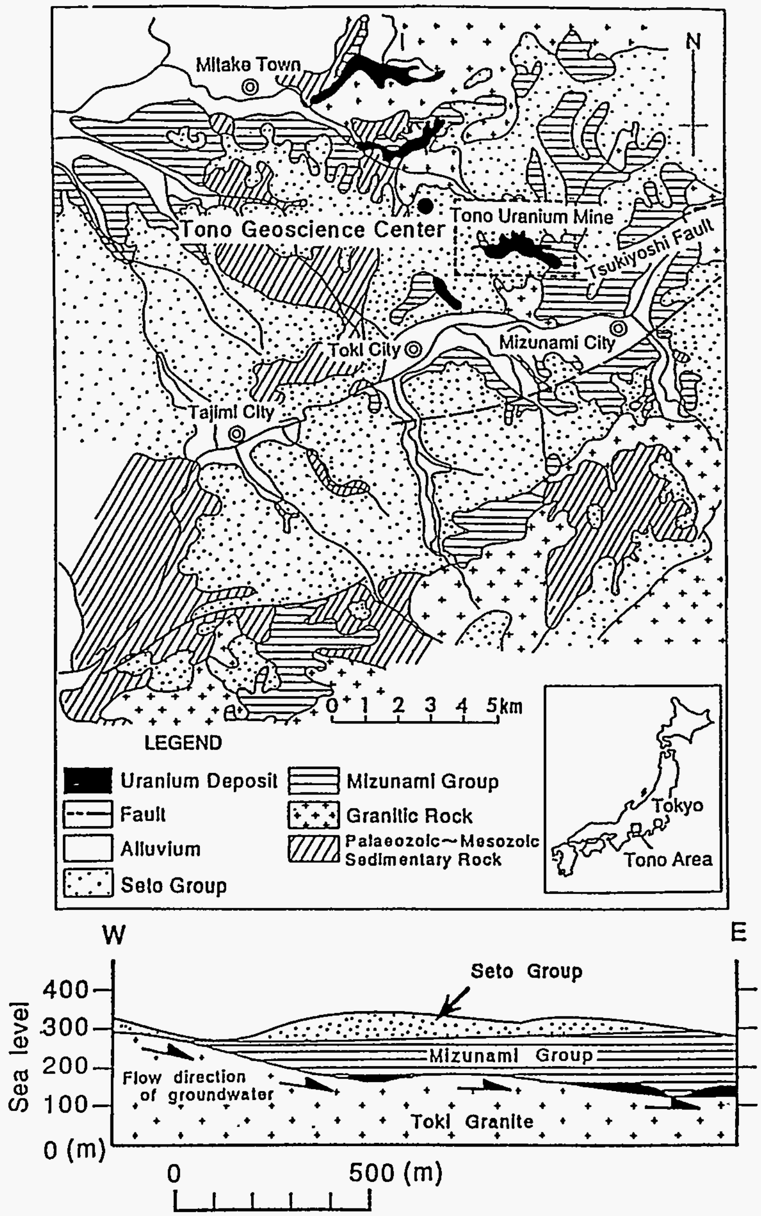


Figure 15.1. Geological and Location Maps of the Tono Mine Region.

The hydrological research being conducted at present includes accumulation of reliable hydraulic data down to a depth of 500 m below ground surface, construction of a hydrogeological model based on survey results, consideration of methods for predicting groundwater flow and evaluation and verification of the groundwater flow model (Fig. 15.2). The results of permeability investigations conducted on Neogene sedimentary rocks and granites in the Tono region indicated that the hydraulic conductivity of sedimentary rocks is higher for coarse-grained formations. The value was approximately on the order of 10^{-8} m/s for medium to coarse sandstones. The hydraulic conductivity of granites is classified into two categories of high permeability (10^{-5} to 10^{-6} m/s) measured in the vicinity of open fractures and low permeability (10^{-8} to 10^{-11} m/s) measured in the unfractured rock mass and in fracture zones filled with clay minerals.

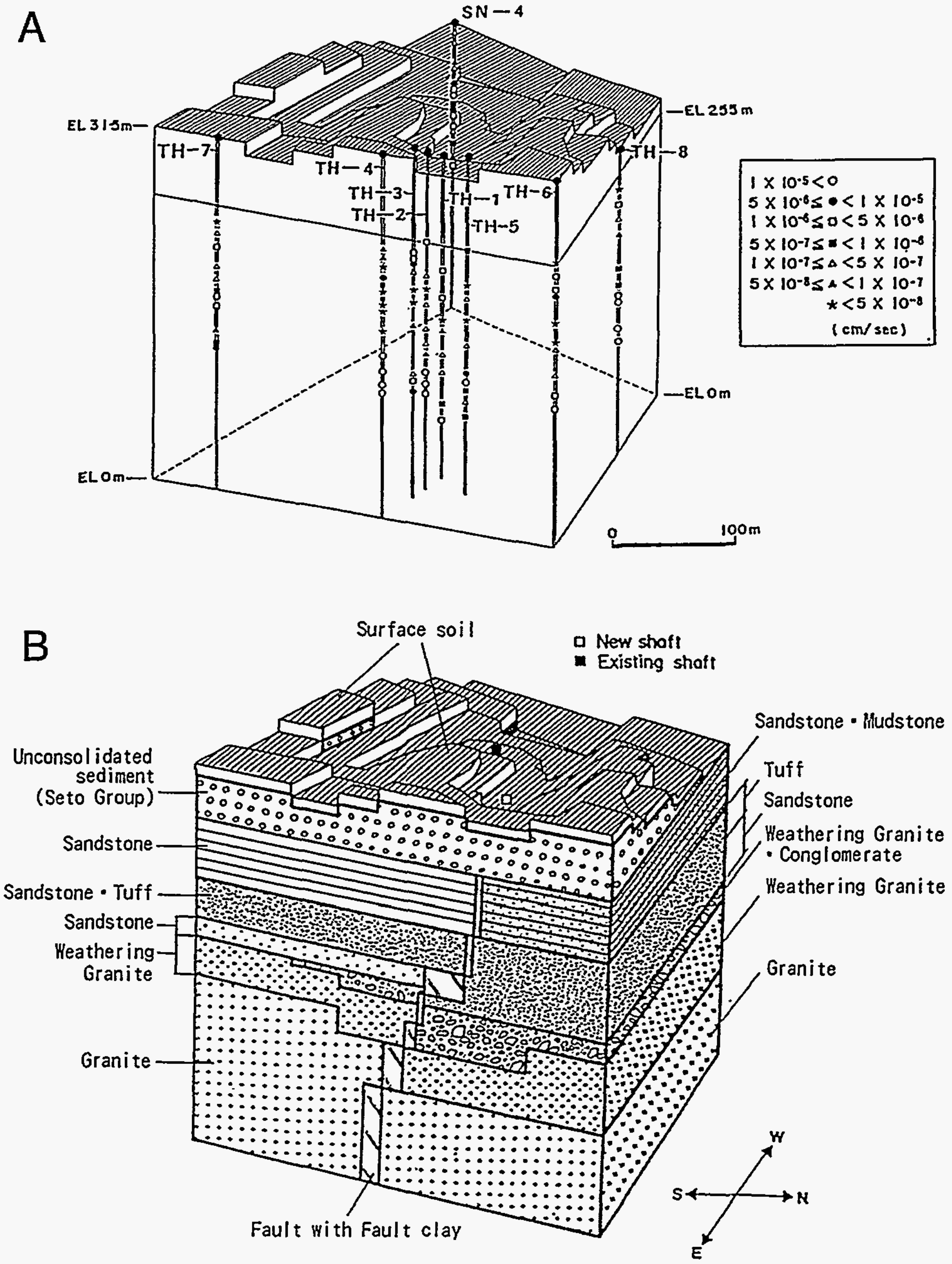


Figure 15.2 A - Hydraulic conductivity distribution, and B - hydrogeological model for the Tono region.

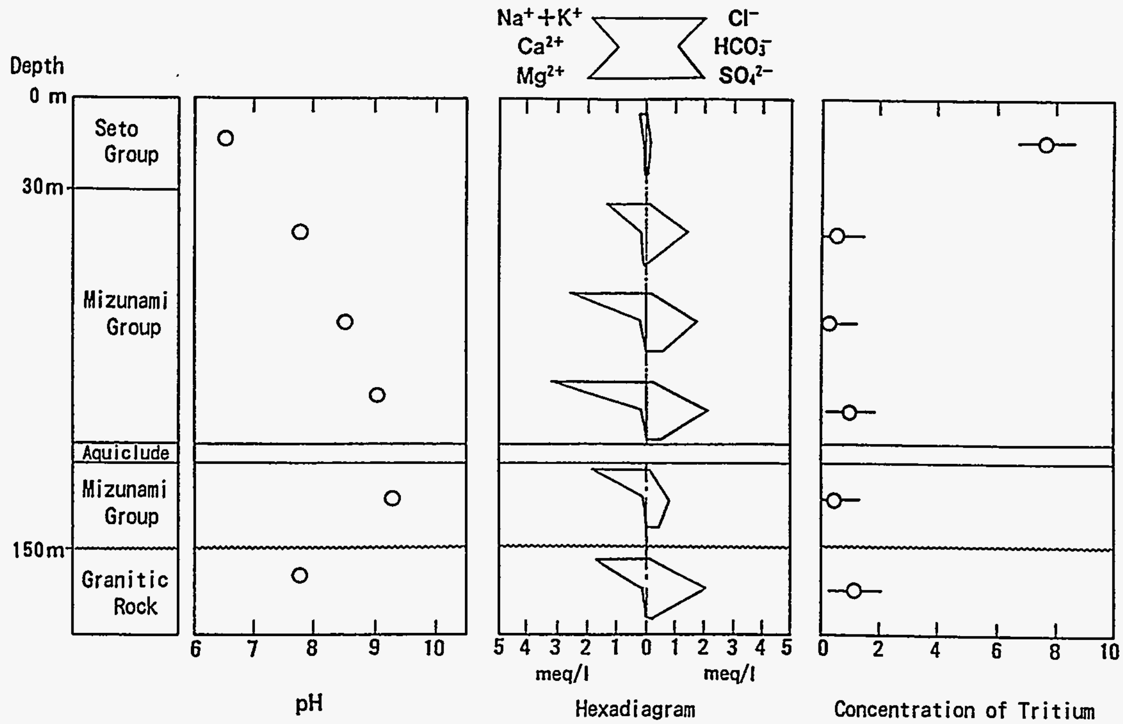


Figure 15.3. Groundwater pH, chemistry and tritium concentration for the Tono region (Major solution components are presented on a hexadiagram.

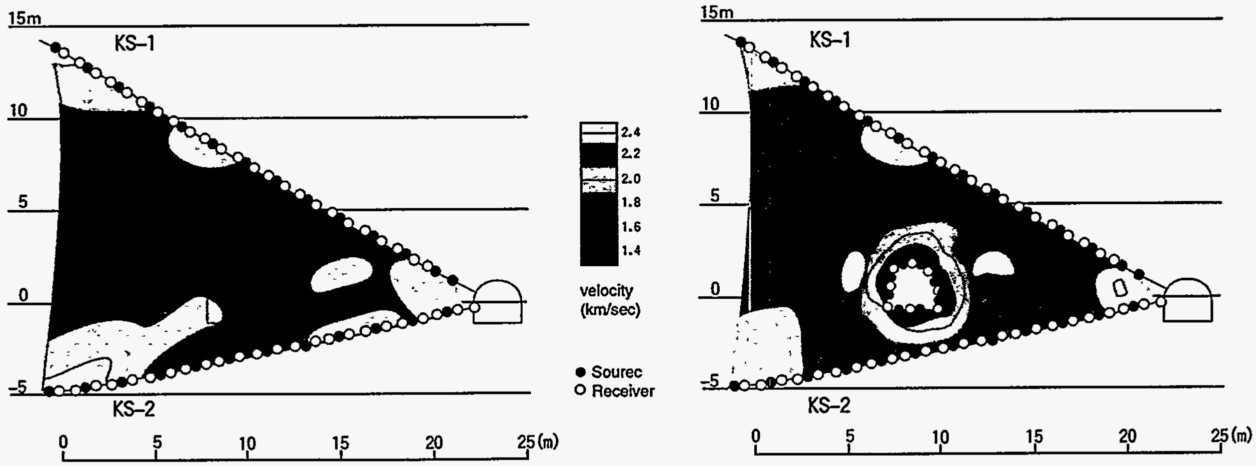
For a three-dimensional analysis of groundwater flow taking the example of the Tono region, piezometric heads are almost hydrostatic except near the surface.The hydraulic gradient is below 0.04 for areas deeper than 500 m underground. The procedure for future research on groundwater flow will be to obtain hydraulic data for depths down to 1,000 m underground, to improve methods for analyzing groundwater flow and to develop suitable investigation methods for a given region.

Geochemical studies aim to determine the age and origin of groundwater and the distribution of geochemical characteristics and to confirm the relevance of the model of the geochemical evolution of groundwater. For this purpose, sampling and analysis of groundwaters from boreholes is being carried out. Groundwaters in sedimentary rocks are mostly the Na-HCO_3 type, and the pH value moves from neutral to alkaline as depth increases (Fig 15.3). A comparative analysis of oxygen and hydrogen stable isotopes confirms the theory of precipitation as the origin of the groundwater.

Radiocarbon dating reveals the groundwater at the base of the sedimentary formations to be at least in excess of 104 years old. The figures for pH, redox potential and concentration of chemical components obtained from a geochemical equilibrium model and from actual measurements in the region agree well with one another. Future tasks are to accumulate geochemical data down to a depth of 1,000 m and to study the geochemical evolution of deep groundwaters, also for granitic rocks (Yamakawa, 1991; Yoshida, et. al., 1994).

To examine solute migration in the deep geological environment, the Tono uranium deposit and its surrounding area are being studied as a natural analogue for migration and immobilization of material within a geological formation. Studies are underway on the environmental conditions for generation and preservation of uranium deposits and on the migration and retardation of natural series nuclides by groundwater flow. Studies so far show that uranium is immobilized in a reducing environment, that the migration and concentration of uranium depends not only on the mineralogy and chemistry of the rocks but also on groundwater flow, and that the uranium found in the ore deposit has not migrated significantly over the past 10^5 years. Future studies should clarify the route of groundwater flow and its relationship with migration of natural series nuclides, and also quantify migration and advance modeling of sorption phenomena.

To ascertain the influence of excavation on the rock formations surrounding a gallery, a series of studies are



(a) Before Excavation of Experimental Gallery

(b) Before and After Excavation of Experimental Gallery

Figure 15.4. Experiment on excavation effects at the Tono Mine.

being conducted in which the original condition of the bedrock is assessed before excavation, followed by prediction of the effect of excavation and, finally, by actual measurement of the effects of excavation (Fig. 15.4). In a study of excavation effects, a shaft with a 6 m inner diameter and 150 m deep has been observed for approximately the past four years. Observations indicate that the "excavation disturbed zone" created by blasting the bedrock extended about 1 m from the shaft wall, while changes in pore pressure extended to a radius of approximately 100 m from the shaft. The next step is to ascertain the effects on different rock types and of varying methods of excavation, as well as to improve the techniques employed in measurement and analysis. It is also necessary to continue monitoring over an extensive period in order to understand the long-term impact on bedrock deformation and hydrology, etc (Sato, et. al., 1995).

15.4.2 Surveys Conducted at Kamaishi Mine

The Kamaishi Mine is an iron and copper mine with granite as the parent rock; it is situated near Kamaishi City in Iwate Prefecture. PNC has been conducting investigations in the Kurihashi granitic diorite since 1988, in a gallery located 550 m above sea level (approximately 300 m below ground surface). In 1993, a second phase was launched for a five-year period in a gallery 250 m above sea level (approximately 700 m below ground surface). The research includes assessment of geological characteristics deep underground, appraisal of the extent of the excavation disturbed zone in the bedrock, hydraulic and migration tests in crystalline rock, testing of engineered barriers and seismic surveys (Fig. 15.5) (Takeda and Osawa, 1993).

In the first five years, the aim was to collect data on the distribution of various characteristics and phenomena occurring in the geological environment. At the same time, the appropriateness of investigation techniques was also tested. Surveys conducted included investigations of fractures in gallery walls and boreholes, physical surveys to ascertain the distribution of fractures, hydrogeological research to assess the permeability of the bedrock, groundwater flow and its modeling, geochemical research to determine the origin, age, chemical evolution, etc., of groundwater, bedrock dynamics to test the effects of gallery excavation, seismic research, and research on engineered barriers.

These studies contribute to improving the understanding of physical properties such as the strength of the Kurihashi granitic diorite, initial stress conditions, the permeability of the bedrock, channeling phenomena whereby groundwater tends to flow along distinct pathways within a fracture, geochemical properties of groundwater deep underground and *in-situ* swelling of bentonite clay as a backfill in bedrock. Studies conducted on the effect of gallery excavation on the geological environment showed that any change in the permeability and deformation of the bedrock occurred within a radius of 1 m from the gallery wall.

Through these studies, it is possible to ascertain the effectiveness of techniques for modeling groundwater flow near the gallery and the deformation behavior of

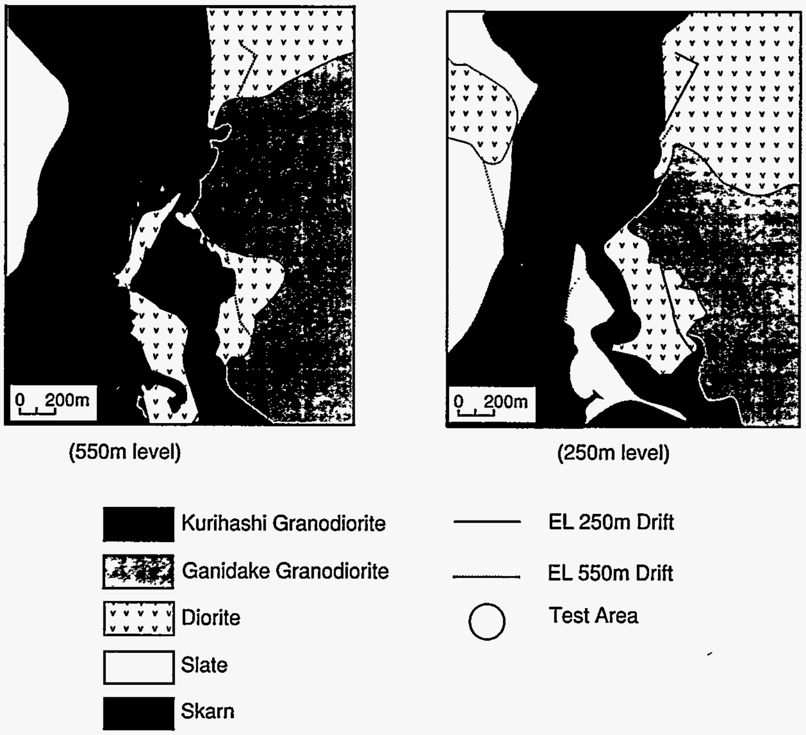


Figure 15.5. Geological map of the *in-situ* experimental site at the Kamaishi Mine.

adjacent bedrock due to the gallery excavation. They also allow validation of radar and resistivity tomography methodology, the derived model of fracture distribution and the technique used for permeability determination.

Seismometers were placed in galleries at different depths to observe seismic-related characteristics; a continuous analysis of pore pressure and the chemical properties of groundwater was also carried out. The results indicate that, for the majority of earthquakes, the rate of acceleration several hundred meters below surface is about half that at the ground surface (Fig. 15.6). Long-term observation of pore pressure and chemical properties of groundwater showed a temporary change at the time of earthquakes, but this was within the range of seasonal fluctuations.

In 1993, a new five-year project was launched to investigate the different characteristics of the deep geological environment and to obtain a more detailed understanding of the range of effects caused by gallery excavation. The work covers geochemical changes occurring within nearby bedrock, the distribution of fractures in the bedrock and galleries, solute migration and water flow, thermal, hydraulic and dynamic interactions between bentonite clay and surrounding bedrock and groundwater, the impact of earthquakes on groundwater flow, and the decrease of earthquake motion with depth.

So far, the studies have shed light on the initial stress conditions at various depths (galleries at 250 m level and 550 m level), the distribution of fractures and microcracks from the viewpoint of mass transport and the redox conditions of groundwater in the vicinity of galleries.

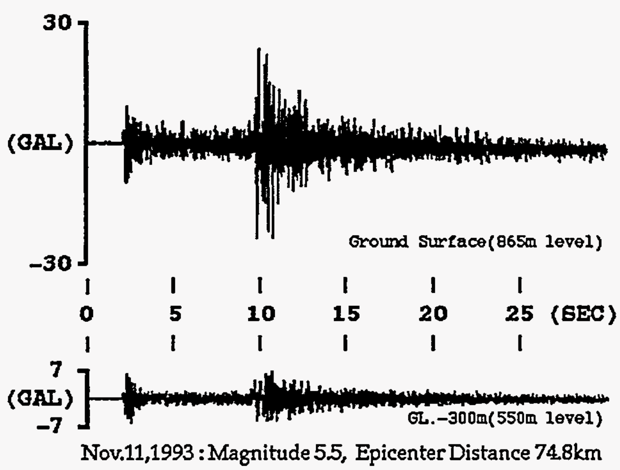


Figure 15.6. Seismic observations at ground surface and underground at the Kamaishi Mine.

15.4.3 Development of Techniques for Investigating Deep Geological Environment

In order to make quantitative measurements of hydraulic parameters deep underground, a hydraulic measurement device designed for conditions of slow water pressure build-up has been developed for application in low permeability bedrock. An *in-situ* measurement device has already been constructed for use at depths down to 500 m and in the order of 10^{-11} m/s for the hydraulic conductivity. Other equipment developed allows a continuous *in-situ* measurement of parameters such as redox potential, pH and dissolved oxygen concentration. With the development of a packer-system in a pressured groundwater sampling device, which is gas-tight, it is now possible to obtain groundwater samples without disturbing their original condition within the rock formation. A new device was completed in 1994; it can be used down to a depth of 1,000 m and is in the process of being tested. Efforts have also been devoted to developing an evapotranspiration device for measuring the distribution of influx volumes from gallery walls and a sinusoidal, crosshole experimental device for use in a single fracture near the gallery wall.

When gathering data in the deep geological environment, it is desirable to do so without disturbing the natural conditions, so as to fully preserve the fractures within the bedrock, the geological structure and hydraulic characteristics. As a consequence, the development and testing of resistivity and seismic tomography are presently underway. Furthermore, a radar technique is being developed, which uses multiple boreholes in order to determine precise fracture zone locations and their extent.

It is also important to improve surface-based methods for predicting conditions in the deep geological environment; the results can then be confirmed using data obtained after excavation of galleries. Research in this area is being carried out jointly by SKB and PNC.

15.4.4 Research on the Long-Term Stability of the Geological Environment

In the first technological report (PNC's Heisei 3 Report), natural phenomena with a potential influence on the geological environment were summarized, suggesting the existence of regionality and regularity in these phenomena. They include earthquake and fault activity, volcanic activity, uplift and denudation, climatic fluctuation and sea-level change. In view of the importance of understanding and predicting the influence of these phenomena on the geological environment, surveys are being conducted of relevant literature published in Japan and abroad (Shimizu, et. al., 1992).

Literature surveys and analyses are performed to first clarify the history of individual natural phenomena. The next step is to conduct research on the nature and scale of the impact of such phenomena on the geological environment and to establish a method for defining a realistic range of fluctuation for the predicted influence of these phenomena.

Regarding fault activity, attention is focused on the possibility of the formation of new faults, by observing the fluctuations in time and space and the locations of fault activity. A method for ascertaining the hydraulic and geochemical fluctuations in groundwater is being considered in order to provide an understanding of the range of influence of fault activity on the nearby geological environment.

To predict the range of variation in uplift and subsidence, it is necessary to have accurate knowledge of past data and an understanding of crustal movements in Japan; a systematic compilation is therefore being made of relevant geomorphological data. To estimate topographic and decreases in the thickness of geological formations, which accompany uplift and subsidence, modeling of denudation and future topographic changes is also necessary.

As for volcanic activity, the characteristics and regionality of Quaternary volcanic activity should be ascertained; the locations of activity as well as the relationship between geological structure, stress fields and plate distribution should also be clarified in order to substantiate the assumption that the region of volcanic activity will not change in the future. Studies should be able to determine the range and scale of thermal impact and its influence on the geochemical characteristics and flow of groundwater.

Studies should be carried out to assess the scale and regularity of climatic and sea-level changes on a global scale.

15.5 CONCLUSIONS

Any discussion of the geological environment of Japan within the context of geological disposal programs requires the development of transparent and logical analytical methods and a systematic accumulation of reliable data. It is also important to make maximum use of existing information. Advances in a new field of research and development, as in the case of this report, should be pursued with the support of public understanding and participation, from the beginning, of experts from all related areas of study; this ensures transparency and steady progress. By way of recognizing the importance of obtaining the consensus of experts from various fields on the overall progress and direction of R & D programs, as well as on individual studies, projects are pursued with constant referral to various commissions.

Regarding sites for research on the deep geological environment, the Atomic Energy Commission of Japan has indicated the desirability of having multiple facilities in view of the wide range of geological features in Japan; this is stated in the "Long-Term Program for Research, Development and Utilization of Nuclear Energy." There is also a clear distinction between plans for an underground research facility and plans for geological disposal. PNC is also aware of the importance of carrying out research, not only in existing galleries, but also in geological environments with undisturbed conditions. It is also important to verify predictive surveys made from the ground surface, following actual excavation of galleries. A research facility which would allow such activities to be pursued is of utmost importance and PNC is devoting considerable efforts toward construction of such a facility as soon as possible.

REFERENCES

Sato, T., K.Sugihara, and H. Matsui, Geoscientific studies at the Tono mine and the Kamaishi mine in Japan, Proc. of 8th International Congress on Rock mechanics, Vol.1, pp. 47-51, 1995.

Shimizu, H., K. Ishimaru, K. Furuya, and Y. Yusa, Natural processes and events relevant to long-term stability of geological environment in Japan, Proc. of the Workshop WC-1 "Waste Disposal and Geology Scientific Perspectives", 29th Internatioal Geological Congress, pp.381-394, 1992.

Shimizu, I., H. Osawa, T. Seo, S. Yasuike, and S. Sasaki, Earthquake related ground motion and groundwater pressure change at the Kamaishi Mine, Engineering Geology Special Publication (in press, 1996).

Takeda, S. and H. Osawa, Current status and future program of in-situ experiments of Kamaishi, Japan, Proc. International Symposium on In-Situ Experiments of Kamaishi, Japan, Nov.11-12, 1993.

Yamakawa, M., Geochemical behavior of natural uranium-series nuclides in geological formation, Proc. Third International Symposium on Advanced Nuclear Energy, pp.150-158, 1991.

Yoshida, K. et al., Data Compilation of Geoscientific Studies of Tono Uranium Deposits, Central Japan, PNC TN 7410 94-15, 1994.

Yusa, Y., K. Ishimaru, K. Ota, and K. Umeda, Geological and geochemical indicators of paleohydrogeology in Tono uranium deposits, Japan, Proc. Workshop in Paleohydrogeological Methods and Their Applications for Radioactive Waste Disposal, OECD/NEA, Paris, 9-10 Nov., 1992.

CHAPTER 16

GENERIC PERFORMANCE AND ENVIRONMENTAL ASSESSMENT OF A RADIOACTIVE WASTE REPOSITORY IN KOREA

Chang Lak Kim, Myung Chan Lee and Jang Soo Nam

Nuclear Environment Management Center, Taejon, Korea

Abstract. The Nuclear Environment Management Center (NEMAC), a subsidiary of the Korea Atomic Energy Research Institute (KAERI), has conducted a performance and environmental assessment of the proposed Korean radioactive waste repository. In this paper, a description is provided of the performance and environmental assessment of a generic Korean radioactive waste repository. A description is given of the various data needed in post-closure performance assessment calculations. The data are divided into four major categories: inventory and design data, chemical data, hydrogeological data, and biosphere data. The results suggest that a generic performance assessment of the conceptual repository may be acceptable when measured against the regulatory criteria. The results indicate, however, that the performance will be strongly dependent on the geology and hydrogeology of the repository location, and it should be noted that the assessment was carried out on the basis of a limited understanding of the site-specific characteristics. It will be necessary to obtain site-specific data at the intended repository location in order to enable a more detailed assessment to be undertaken. This preliminary assessment of the conceptual repository provides a firm foundation for future site-specific assessment activities.

16.1 INTRODUCTION

The radioactive waste management program in Korea dates back to mid-eighties when KAERI perceived, from prior studies, the necessity for a national program for a comprehensive and systematic management of radioactive wastes including spent fuel arising from this country's ambitious nuclear power plant program. The recommendation therefrom was taken in consideration by the Korea Atomic Energy Commission which made a decision at its 221st meeting in 1988 to establish a relevant program to be implemented. Institutional arrangement for this program was that the required waste fund be levied on waste generators by the "polluter pays" principle. Initial works of the program had been implemented, including conceptual design of a low-level radioactive waste repository and the development of transport casks, until the whole program has been seriously hindered by the difficulty of site acquisition.

The major difficulty in site acquisition came from opposition of local communities at potential sites. The bad image of waste burial, combined with fear of potential nuclear danger, seems to have made the local communities abhorrent to any attempt to access the sites as culminated by the Anmyon Island incident in late 1990, where a series of demonstrations by local residents influenced the government to cancel the nomination of the site. All the efforts of NEMAC and the government to convince the local communities of potential sites have failed in a social mood overwhelmed by the NIMBY syndrome and an anti-nuclear movement. At the end of 1994, the government nominated Guleop Island, with only nine residents, as the candidate site for the repository and later finalized it as the official site. However, even after the governmental announcement, a series of demonstrations by the residents of Dukjuk Island, mother island of the smaller Guleop Island, acted as big obstacle against the government and NEMAC. The final blow against the Guleop Island Project was made at the end of 1995 by the confirmation of active fault zones, near and on the island, so that the government had to announce the cancellation. After a decade of unsuccessful efforts in search of a site, the government decided to amend the institutional approach to the problem.

In this paper, the groundwater pathway results of a performance and environmental assessment study[1] of the conceptual Korean radioactive waste repository, carried out jointly by NEMAC and AEA Technology from 1994 to 1995, are summarized.

In Section 16.2, a description is given of various data used in the assessment calculations. In Section 16.3, a description is given of the assessment calculations undertaken to address radionuclide transport along the groundwater pathway; this was the major component of the post-closure performance assessment. However, the results of the assessment carried out to address the effects of gas generation and migration on the performance of the proposed Korean repository and the calculations carried out to address the radiological risks arising from inadvertent human intrusion into the proposed repository are not included in this paper.

16.2 PREPARATION OF ASSESSMENT DATA

16.2.1 Design and Inventory Data

Radioactive wastes requiring treatment and disposal in Korea are dominantly produced by operation of the civil nuclear power reactors. These are of the PWR and CANDU types, and produce a range of wastes in the low- and intermediate-level categories. Spent fuel is not considered at this time.

The levels of radioactive contamination vary widely, and a proportion of each of the first three waste types appears in both the LLW and ILW categories. The choice of waste treatment technologies reflects this variation.

The liquid concentrates come from the treatment of water discharged from the primary reactor circuit, the secondary heat transfer circuit, and the spent fuel storage pools. The water is treated so that dissolved contaminants are precipitated, and it is then evaporated to reduce the volume. Using current technology, the resulting 'sludge' is mixed directly with cement and poured into 200-litre disposal drums. In the near future, material may be evaporated to dryness and disposed in drums containing a paraffin wax encapsulation matrix.

The ion exchange resins arise from in-service clean-up of the water circuits and spent fuel pool. When they have served their useful life, they are discharged and treated for disposal. Using the current technology, resins are cemented directly into 200-litre drums. In the future, resins will be dried and loaded into high-integrity containers (HIC), composed of stainless steel, which will be welded shut.

The spent filters arise from various air and water filtration uses around the power plants. Some of them are of the HEPA type and consist largely of paper. All filters are treated in the same manner, by direct cementation into 200 litre drums.

General contaminated trash arises from day-to-day operations at the power plants, and consists of contact clothing, wipes, sample containers, redundant equipment and tools, etc. Some of this material may not be contaminated at all, but the general policy is to prevent accidental spread of contamination by treating all waste from the active area as if it were radioactive. These wastes will be loaded into 200 litre drums, and subjected to high-force compaction, reducing their volume by a factor of three or more. The resulting 'pucks' will then be loaded into larger overpack drums (of about 300 litre capacity) for disposal.

Korean repository design

The conceptual design of Korean repository[2] (for the initial phase of the repository construction) consists of the following five caverns, as illustrated in Figure 16.1:

a. LLW (Type I) cavern;
b. LLW (Type II) caverns (two caverns);
c. LLW (Type III) cavern; and
d. ILW cavern.

The cross-sectional designs of the LLW and ILW caverns are illustrated in Figures 16.2 and 16.3, respectively. Physical parameters defining the cavern and disposed waste volumes are given in Table 16.1.

It should be noted that no decision has yet been made concerning the backfilling strategy to be adopted in the ILW cavern. The implications for repository performance of various backfilling strategies for the ILW cavern were addressed in this performance assessment. These strategies consist of:

a. cementitious backfill;
b. 10% bentonite / 90% crushed rock mixture; and
c. no backfill.

Waste inventory

Summary information for each of the radionuclides appears in Table 16.2. A summary of the number of drums in each cavern associated with each waste type

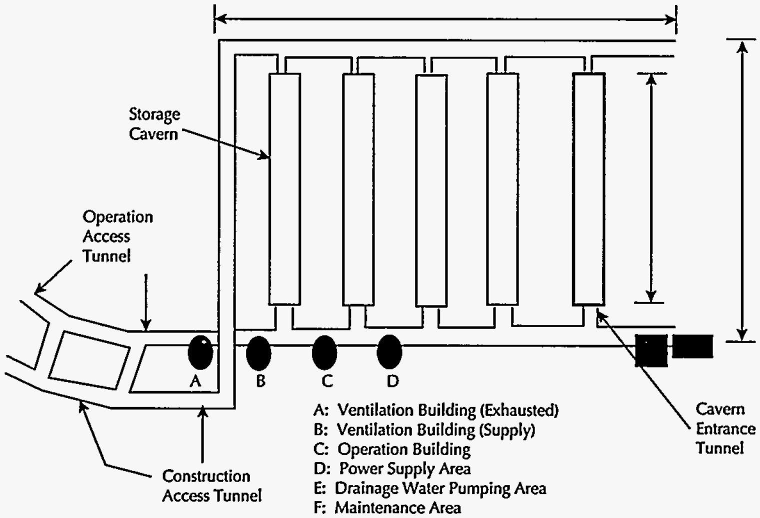


Figure 16.1. Proposed layout of Korean repository (Initial Phase).

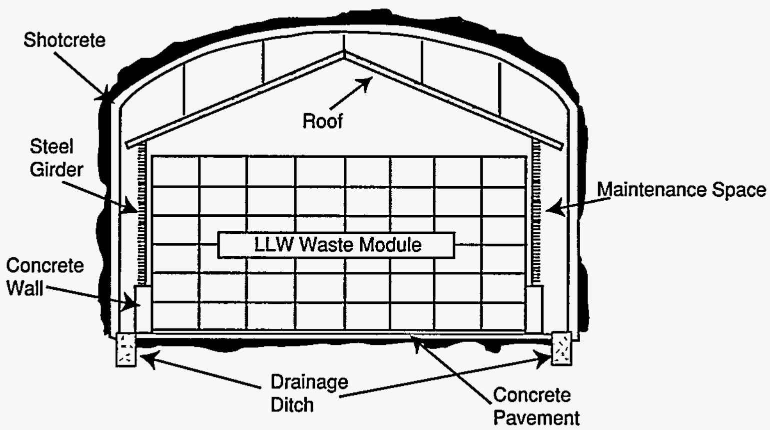


Figure 16.2. Cross section of LLW cavern.

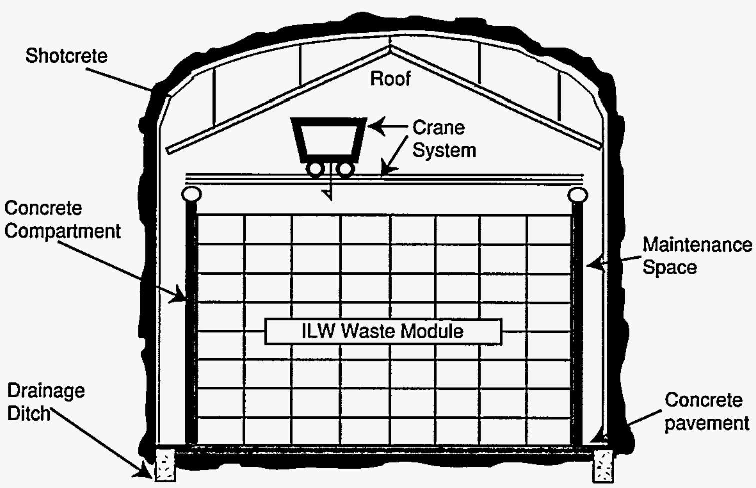


Figure 16.3. Cross section of ILW cavern.

Table 16.1. Cavern and disposed waste volumes (m^3).

Parameter	LLW (Type I)	LLW (Type II) (total)	LLW (Type III)	ILW
V_{wst}(a)	3.85 10^3	7.26 10^3	3.37 10^3	5.52 10^3
V_{dmod}(b)	1.08 10^4	2.15 10^4	1.08 10^4	1.49 10^4
$V_{b/f}$(c)	-	-	-	3.05 10^4
V_{exc}(d)	2.73 10^4	6.06 10^4	3.03 10^4	5.62 10^4

Notes:
(a) Volume of packaged waste in 200 litre containers.
(b) Volume of disposal module (6-pack LLW) or 8-pack (ILW).
(c) Volume of backfill (ILW only).
(d) Total volume of caverns.

and of the total volume occupied by the wasteform is provided in Table 16.3.

16.2.2 Chemical Data

Calculations have been carried out to investigate the chemistry of the JWS-2 groundwater, collected at a depth of 330 m, which was considered to have a chemistry most analogous to that in the vicinity of the study area. The aqueous speciation of this groundwater and the likelihood of certain minerals precipitating or dissolving has been modelled using the HARPHRQ program[3] with the HATCHES database[4]. Further calculations have been performed to predict the effect of groundwater equilibration with a high-calcium cement. These calculations have been used as the basis for determining the solubility of a number of key radionuclides in two groundwaters, the JWS-2 water at pH 5.7 and a cement-equilibrated water at pH 12.9.

Table 16.2. Radionuclide Inventory.

Radionuclide	Half-life (years)	Inventory (Bq)
^{3}H	1.24 10^1	4.31 10^{12}
^{14}C	5.73 10^3	4.11 10^{12}
^{60}Co	5.27 10^0	6.16 10^{14}
^{59}Ni	7.50 10^4	1.02 10^{13}
^{63}Ni	9.60 10^1	3.12 10^{14}
^{90}Sr	2.91 10^1	7.95 10^{12}
^{94}Nb	2.03 10^4	2.46 10^{11}
^{99}Tc	2.13 10^5	3.34 10^{11}
^{129}I	1.57 10^7	1.93 10^{10}
^{137}Cs	3.00 10^1	3.41 10^{14}
^{235}U	7.04 10^8	1.11 10^7
^{238}U	4.47 10^9	3.91 10^8
^{238}Pu	8.77 10^1	1.59 10^{11}
^{239}Pu	2.41 10^4	3.28 10^{11}

The PDFs for elemental solubility limits that were used in this assessment were centred on the results of the HARPHRQ speciation calculations, with log-triangular PDFs covering whole orders of magnitude. The main materials of interest to the conceptual repository are the in-drum cement, concrete and bentonite (candidate backfill materials for the ILW caverns), and the mineral andesite, which is the host rock considered for this study.

A literature survey has been carried out to determine the likely Rd values for sorption of radionuclides onto the

Table 16.3. Waste inventory.

Waste type	Number of drums	Volume occupied (m^3)			
		LLW (Type I)	LLW (Type II)	LLW (Type III)	ILW
Liquid conc. in cement	10,425	-	4,996	-	3.08 10^3
Liquid conc. in paraffin	-	-	-	10,273	2.05 10^3
Ion exchange resin in cement	4,516	-	-	-	9.03 10^2
Ion exchange resin in HIC	-	-	-	16,445	3.29$10^3$
Spent filters in cement	4,307	-	-	882	1.04$10^3$
General trash	-	36,288	11,868	-	9.63 10^3

bentonite backfill and onto the host rock formation.

16.2.3 Hydrogeological Data

The first step in the development of a numerical model of the groundwater flow in the region around the study area is to develop a conceptual model of the geological and hydrogeological structure of the region. The general direction of groundwater flow in the region around the hypothetical repository location would be from the high ground inland towards, and roughly perpendicular to the coast. The most appropriate type of model to construct for this illustrative assessment was therefore a two-dimensional vertical cross-section model along a line roughly perpendicular to the coast. It was noted that the model would have to extend some distance offshore so that the saline transition zone near the coast could be modelled satisfactorily. The geological structure along the main line of section selected for the groundwater flow model is shown in Figure 16.4.

In order to carry out this preliminary assessment, input PDFs were required for all of the hydrogeological properties used in the groundwater flow and transport models. The materials identified in the geological structure were:

1. upper andesite;
2. lower andesite;
3. fractured lower andesite;
4. granite;
5. shale;
6. sandstone/mudstone/siltstone sediments; and
7. gneiss.

In addition, the hydrogeological properties of the repository itself, and of the access tunnels, had to be considered. A PDF was required for the permeability and porosity of the material in three cases: normal rock, rock within a fault core, and rock within a fault halo. The notation T(a,b,c) is used to indicate a triangular PDF with upper and lower limits c and a, respectively, and peak value b. For convenience, logarithms to base 10 were used. The hydraulic conductivity for some of the rock types are summarized in Table 16.4, as an example.

16.2.4 Biosphere Data

The approach adopted is to identify critical groups, and hence to evaluate potential maximum individual risks. This evaluation is based on the definition of hypothetical subsistence communities, which are assumed to make maximum reasonable use of local food resources and to be located in the area of the environment assessed to be the most contaminated as a result of possible future discharges from the repository.

In this assessment, the screening process was carried out using the generic biosphere program BIOS_3A[5], which considers a relatively wide range of potentially important pathways. On the basis of the screening calculations, a simple process model was developed taking advantage of the Compartment Biosphere submodel available within the MASCOT program[6].

The terrestrial biosphere considered comprises the catchment of a small river discharging into a coastal sea. The section of river that may be contaminated by

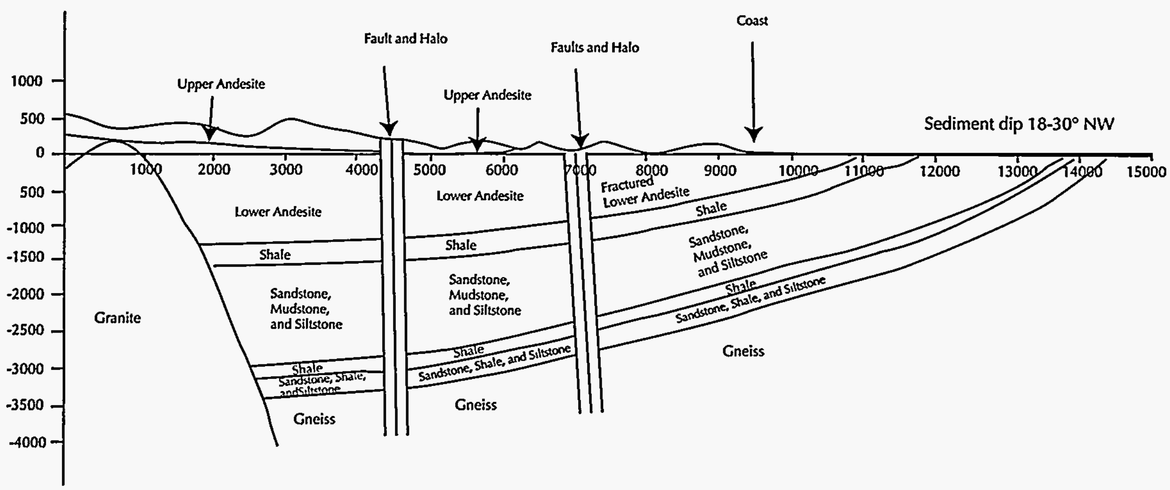


Figure 16.4. Geological structure along the line of the model cross section. Distances and elevations in metres.

Table 16.4. Summary of log-hydraulic conductivity distributions.

Rock type	Log-hydraulic conductivity(a) Lower bound	Peak	Upper bound	Comment
Andesite	-12	-8	-6	Isotropic
Fractured Andessite	-11	-7	-5	Isotropic
Granite	-11	-8	-6	Isotropic
Gneiss	-13	-10	-7	Isotropic
Shale	-12	-9	-7	Isotropic
Sandstones	-10	-7.6	-5	Isotropic

Note: (a) Values given are for log-hydraulic conductivity (permeabilities in m s^{-1}, log to base 10).

groundwater from the repository, either directly or indirectly (through drainage from adjacent farmland), is estimated to be 5 km in length, and the area of its associated catchment, 10 km^2.

The critical group at risk from radionuclides entering the biosphere is assumed to be a community of subsistence farmers who live and work in the land. For the preliminary assessment, their diet was assumed to be similar to the Korean average.

The endpoint of the calculations corresponds to the maximum dose received resulting from a steady 1 Bq yr^{-1} release rate from the geosphere, which occurs as concentrations in the environment approach, steady-state equilibrium values. The calculations demonstrated that a wide range of terrestrial pathways should be considered. Marine pathways, however, were found to be less important, because of much higher levels of dilution in coastal waters. The results of the analysis using BIOS_3A provided a basis for selecting pathways for the second phase of the assessment using MASCOT's biosphere compartment submodel facility. Terrestrial pathways considered in the second stage of the assessment using MASCOT included ingestion of rice and vegetables, drinking water, consumption of meat products (beef, milk, liver, and poultry), external gamma exposure from soil, and dust inhalation. Although less important, ingestion of marine foodstuffs was also considered.

Figure 16.5 shows the structure of the biosphere model developed for the preliminary assessment.

16.3 GROUNDWATER PATHWAY

16.3.1 Groundwater Flow Modelling

After the closure and resaturation of a repository for radioactive waste, it can be anticipated that radionuclides will dissolve in groundwater flowing through the wasteform and will be transported with the groundwater through the geosphere to the biosphere. This is the natural pathway by which radionuclides, disposed in a repository, may return to the human environment. It is almost certain that radionuclides will return to the biosphere by this route, and so an analysis of the risk arising from the groundwater pathway forms an important part

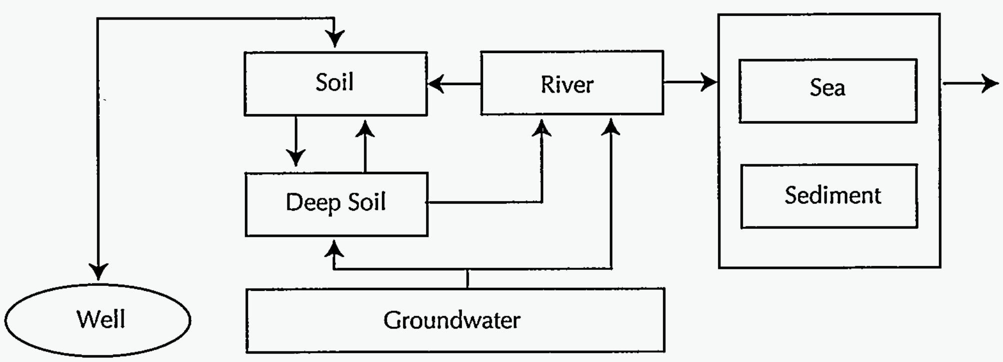


Figure 16.5. Structure of biosphere model.

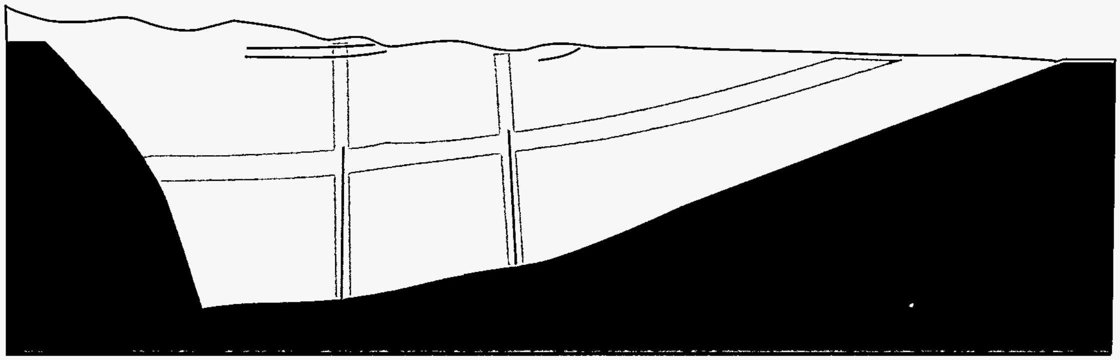


Figure 16.6. Shade plot of the NAMMU patch grid showing assignment of rock types. The lines from the repository locations represent the access tunnels.

of an assessment of the performance of a repository for radioactive waste.

In order to carry out this analysis, it is necessary to be able to estimate the rate of groundwater flow in the vicinity of the repository (which largely determines the flux of radionuclides leaving the repository) and the nature of the regional groundwater flow system (which determines the subsequent transport through the geosphere and return to the biosphere).

The first stage in the development of a NAMMU groundwater flow model[7] of the site is the construction of a finite-element mesh that represents the important features of the geology and topography of the site (see Fig. 16.4) and extends to regions where well-defined boundary conditions can be identified. Careful design of the finite-element mesh is necessary both to ensure that the numerical solution is as accurate as possible and to allow for subsequent changes to the model to be made with ease.

The top surface of the mesh was a smoothed representation of the topography, treated as a number of straight-line segments that preserved the major features. The left-hand boundary of the model was taken to be an assumed (vertical) groundwater divide under the high ground inland.

The gneiss has a very low permeability and so, in principle, the base of the sediments could have been taken to form the base of the model. However, a satisfactory treatment of the region of saline groundwater offshore would require that the distribution of salt concentration on the base of the sediments be known a priori, which is not the case. It was therefore preferable that the model extended far enough offshore to include the offshore surface outcrop of the gneiss. It is then reasonable to assign a constant salt concentration along the right-hand boundary of the model. Figure 16.6 shows the assignment of rock types in the base-case model. The aim was to produce a grid in which the largest elements were about 200-250 m across. In practice most of the elements are considerably smaller. The final grid used for the calculations is shown in Figure 16.7.

The overall (large-scale) flow is driven by the high heads produced by the high ground on the left-hand side of the model and moves downwards towards the right-hand side of the model. This flow continues at depth until it reaches the salt front, which is intruding from the right-hand side of the model. The saline transition zone is at the point where the driving head from the topography exactly balances the head due to the increased density of the seawater. The freshwater therefore flows up the salt front and discharges near the coast. Seawater intrudes from the right-hand boundary of the model and flows into the model until it reaches the saline transition zone, which it flows up before discharging through the sea bed. In the near-surface part of the model onshore, small flow cells driven by local topographic variations are superimposed on the large-scale flow. Local discharge occurs in all of the small valleys represented in the model. There is very little flow in the gneiss layer.

A series of pathline calculations were performed to investigate the general nature of the flow system. The pathlines that were used for the MASCOT analysis were started from the following two sets of points: (3600,55), (3700,55), and (3800,55) to represent paths starting from the 'upper repository' (i.e. a repository located 50 m above OD, about 250 m below the ground surface), and (3600, - 50), (3700, - 50), (3800, - 50) to represent pathlines starting from the 'lower repository' (i.e. a

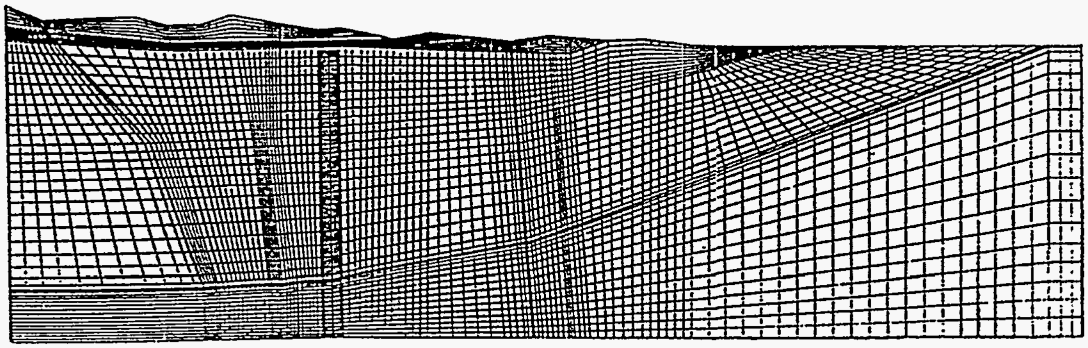


Figure 16.7. Plot of finite-element mesh.

repository located 50 m below OD, about 350 m below the ground surface). The travel times and path lengths for these paths, and the specific discharges at the repository locations, are summarized in Table 16.5.

One of the pathlines that was started from the upper repository position crossed the fault zone near the repository and emerged near the tunnel entrance after a travel time of approximately 1200 years. The other two pathlines from the upper repository position emerged up the fault zone with travel times of approximately 500 years after being caught in the flow cell that discharges in the small valley near the fault (Fig. 16.8a). All three pathlines that started from the lower repository crossed the fault and emerged near the tunnel entrance with travel times of about 1100 years (Fig. 16.8b). Three pathlines were also started from a location near the coast, solely in order to illustrate the general nature of the flow in the vicinity of a hypothetical repository sited there. Two of the pathlines emerged a short distance offshore, but the third was caught in a local flow cell and emerged in the valley closest to the coast (see Fig.16.8c).

Finally, a calculation was performed to estimate the resaturation time of the repository. The base-case model was modified to apply a boundary condition of atmospheric pressure at the repository location. The total flow of groundwater into the repository induced by this condition was then estimated by integrating the specific discharge along the four sides of a box closely matching the repository location, and then multiplying the result by the width of the repository perpendicular to the cross section. The resaturation time is then estimated by dividing the empty volume of the repository by the volume of flow towards the repository.

The total flow into the repository in the two-dimensional model was found to be 4.67 10^{-6} m^2s^{-1}. The repository region was taken to have a length of 440 m perpendicular to the section, giving a total flow into the repos-

Table 16.5. Results of the base-case pathline calculation.

(a) Upper Repository

Path	Travel time (years)	Pathlength (m)	Repository specific discharge (x component, m s^{-1})	Repository specific discharge (y component, m s^{-1})
1	1176.2	1828.6	1.2265 10^{-9}	-8.684 10^{-10}
2	565.93	971.61	1.3302 10^{-9}	-6.9320 10^{-10}
3	432.12	777.98	1.3916 10^{-9}	-5.1647 10^{-10}

(b) Lower Repository

Path	Travel time (years)	Pathlength (m)	Repository specific discharge (*x* component, m s^{-1})	Repository specific discharge (*y* component, m s^{-1})
1	1243.1	1882.9	1.0702 10^{-9}	-7.4150 10^{-10}
2	1114.8	1722.3	1.1650 10^{-9}	-6.0711 10^{-10}
3	1049.1	1602.4	1.2276 10^{-9}	-4.6845$10^{-10}$

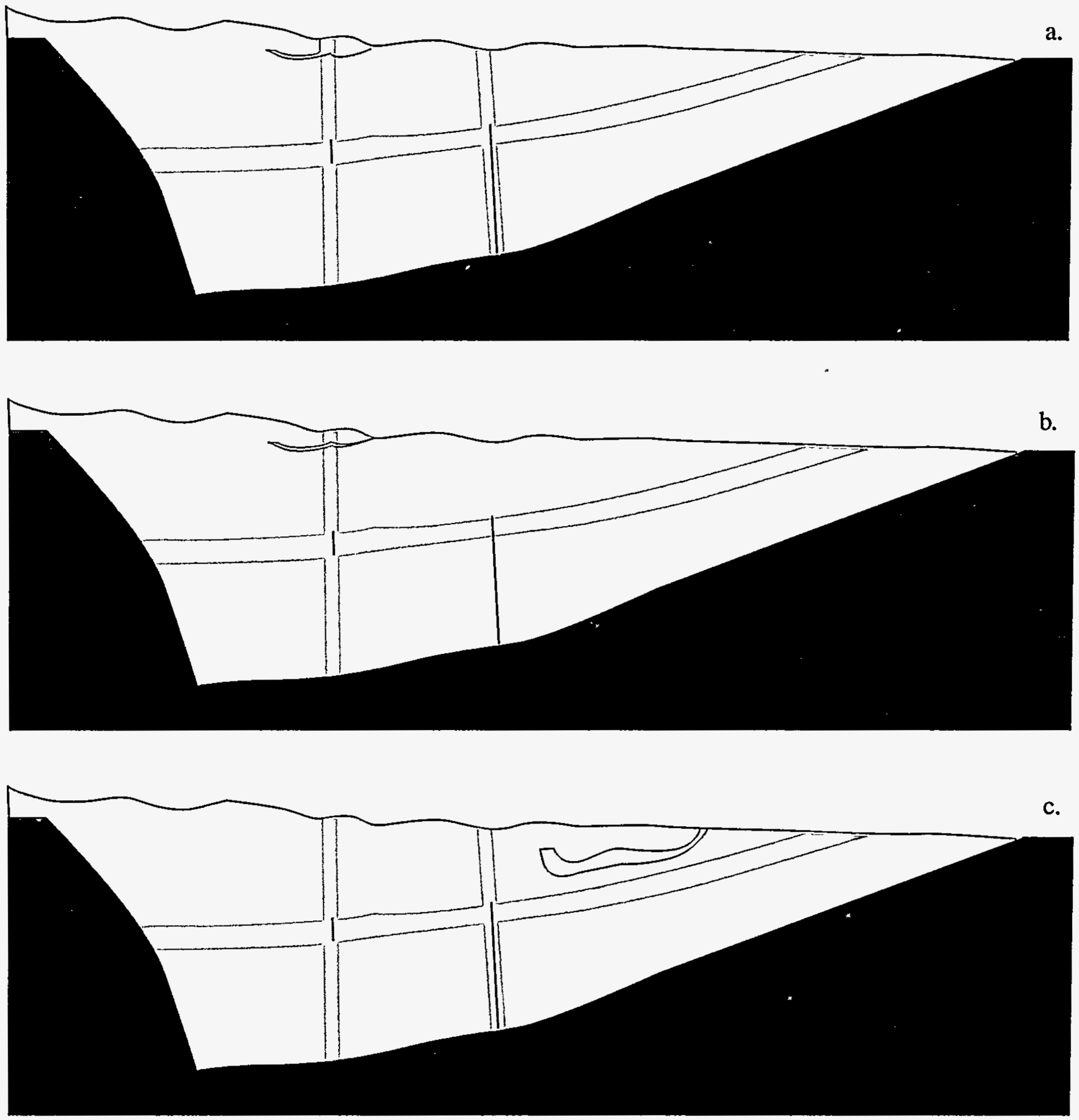


Figure 16.8. Results for some key pathlines: a - From the upper repository position; b - From the lower repository position, and c - From the coastal repository position.

itory region of 2.05 10^{-3} m^3s^{-1}. The total empty volume of the caverns after repository closure is 1.54 10^5 m^3, which gives a resaturation time of 2.4 years. This short time is a result of the high heads above the repository location and the relatively high permeability of the andesite. It should be noted that as the repository resaturates, its pressure will rise and the inflow will be correspondingly reduced. Thus, the value given above is likely to be an underestimate of the resaturation time.

16.3.2 System Model for Groundwater Pathway

In this subsection, the construction of an overall model of the system for groundwater-mediated return of radionuclides to the biosphere is explained.

Source-term submodels

The repository under consideration is planned to contain wastes of several different types, and there will be some degree of segregation into different parts of the repository. The different waste types can therefore be expected to contribute differently to the source term. In general, the key factors determining source-term behaviour are:

a. degradation of the physical containment;
b. chemical control on the solution concentration of the

Table 16.6. Calculated buffering times for caverns.

Cavern	Amount of CaO (mol m^{-3})	Buffering time at pH12.2 (yr)
LLW (Type I)	975	$1.5\ 10^3$
LLW II	0	0.0
LLW III	218	$3.3\ 10^2$
ILW (no backfill)	20	$3.2\ 10^1$
ILW (bentonite backfill)	20	$3.8\ 10^4$
ILW (concrete backfill	2,400	$4.6\ 10^6$

radionuclides; and

c. the rate of groundwater flow through the repository.

Although physical containment of the wastes is important during the operational phase of the repository, the long-term behaviour after closure will be affected significantly by physical containment only in the case of containers specially engineered for exceptional performance. It is recommended that for all wastes in 200 - litre mild steel drums, physical containment be ignored, since all the other time scales involved in release and transport of radionuclides will be much longer than the expected corrosion lifetime of these drums. For the ion exchange resins in stainless steel HIC containers, however, a period of absolute containment should be modelled.

Some of the source term models selected for analysis of the release of radionuclides take account of the conditioning of the pore water to high pH by dissolution of free calcium hydroxide in the cements. It is appropriate to analyse each disposal vault, to determine whether there is sufficient $Ca(OH)_2$ to buffer the pH during the relevant assessment period.

The results of a simple analysis are given in Table 16.6 for each type of disposal vault; note that the buffering times are averaged across the entire vault, and do not represent the smaller-scale buffering within packages. This analysis indicates that the current plans would result in a wide range of buffering times for the various vaults. The LLW I and backfilled ILW vaults would clearly be buffered for a substantial length of time, whereas the LLW II and non-backfilled ILW vaults would not. The LLW III vaults represent an intermediate case. It is clear that extended buffering of pore water to high pH would require either increased amounts of free $Ca(OH)_2$, or reduced groundwater flow through the vaults (most easily achieved by backfilling).

Because the six types of waste are distributed in different caverns, it was necessary to adopt an approach in which nine different source-term submodels were used, as shown in Figure 16.9.

The submodels LLW1A, LLW1B, etc. are MASCOT Containment submodels, which are used to specify the initial inventory of each radionuclide, and any time of absolute containment of the waste. These feed into source-term submodels, ST1A, ST1B, etc., which calculate the release of the radionuclides. The purpose of each of these submodels is summarized in Table 16.7.

In Figure 16.9, the submodels named DIST1 and DIST2 are Distributor submodels used in MASCOT for combining and/or redistributing fluxes between submodels. In this case, DIST1 adds the outputs of the three ILW source-term submodels to provide the input to submodel BARR, which represents the barrier provided by the backfill in the ILW cavern. Finally, DIST2 adds the output of BARR and those of all the LLW caverns to make the total source-term output to be fed into the Geosphere section of the system model.

The BARR submodel is added to represent the time delay for release of radionuclides from the ILW cavern into the geosphere, arising because of the backfill in that cavern. For initial calculations, it was decided to treat the effect by using a porous geosphere submodel, with nominal water transit time equal to the approximate time for water molecules to diffuse through the barrier. The different radionuclides would then be transported through this barrier submodel in times longer than this, according to their retardation coefficients, calculated from sorption distribution coefficients appropriate to the backfill material.

Geosphere transport submodels

From the pathline calculations, two possible pathways from the repository to the surface emerged; the first (Path A) spending time in the upper/lower andesite, followed by a time crossing the fault zone, followed by a further time in the upper/lower andesite, the second

Table 16.7. Source-term submodels within MASCOT system model.

Name	Submodel type	Representing
ST1A	SLST[(a)]	Cemented liquid concentrates (LLW cavern Type I)
ST1B	SLST[(a)]	Cemented ion-exchange resins (LLW cavern Type I)
ST1C	SLST[(a)]	Cemented filters (LLW cavern Type I)
ST2	SLST[(a)]	Compacted trash (LLW cavern Type II)
ST3A	SLST[(a)]	Cemented liquid concentrates (LLW cavern Type III)
ST3B	SLST[(a)]	Compacted trash (LLW cavern Type III)
ST4A	Leaching	Paraffin-encapsulated liquid concentrates (ILW cavern)
ST4B	Leaching	Ion- exchange resins in HIC (ILW cavern)
ST4C	SLST[(a)]	Cemented filters (ILW cavern)

Notes: (a) Solubility-limited source term.

(Path B) spending time in the upper/lower andesite followed by a time travelling vertically up the fault zone to the surface.

The network of geosphere submodels is shown in Figure 16.9. The input to the geosphere network is a combined flux from all the source terms (from submodel DIST2. The distributor submodel DIST3, divides the flux leaving the AND1AB submodel (representing the first section of andesite that occurs in both paths) into two parts, one which takes Path A (to submodel FAULTA), and one which takes Path B (to submodel FAULTB). The fluxes from the two paths are recombined in submodel DIST4 to provide a total flux to the biosphere. The geosphere submodels represent the following:

AND1AB The first section of upper/lower andesite in which both paths A and B spend time;

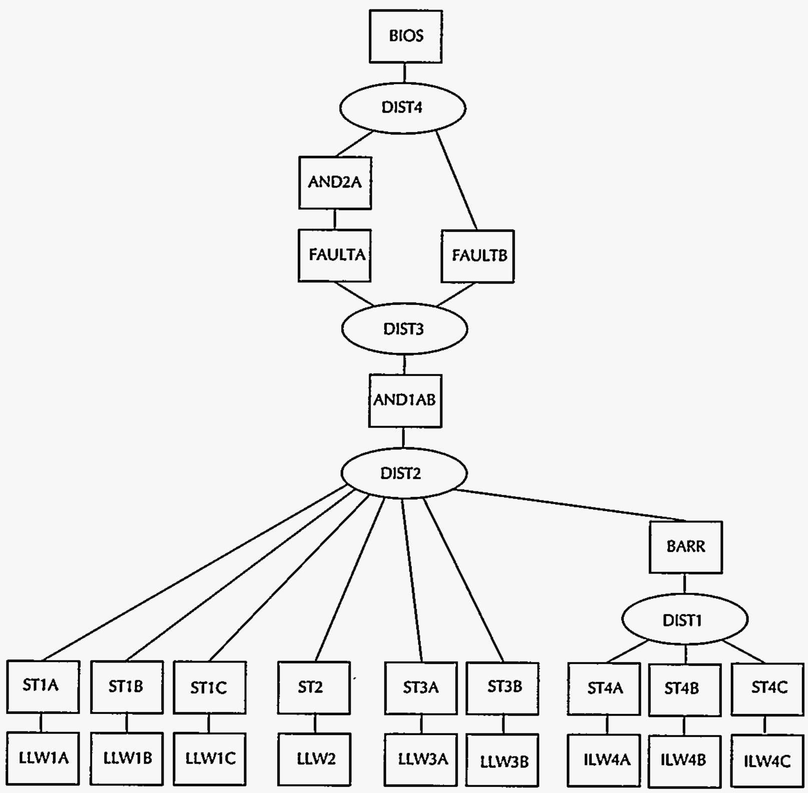


Figure 16.9. System model made up out of source term, geosphere, and biosphere submodels.

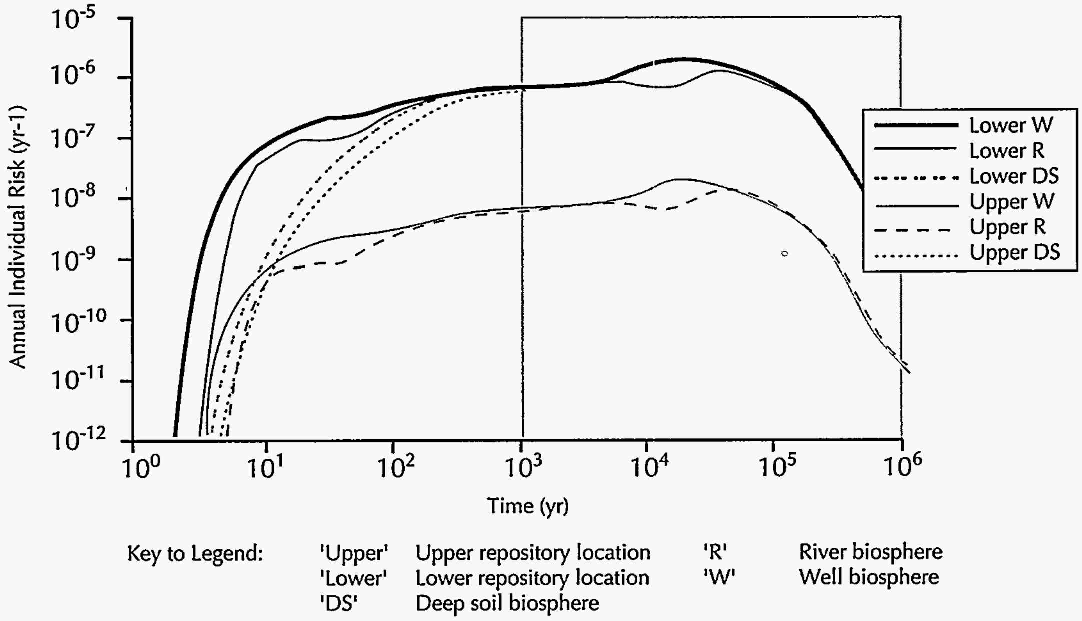


Figure 16.10. Total annual individual risk as a function of time for the upper and lower repository locations for each biosphere.

FAULTA Path A in the fault zone;
FAULTB Path B in the fault zone to the surface;
AND2A Path A in the second section of upper/lower andesite to the surface.

All these submodels are MASCOT Porous Geosphere submodels. This type of submodel assumes that the rock matrix is fully accessed and hence the porosity is the full matrix porosity.

Biosphere submodels

Three exposure pathways were considered, in which the flux from the geosphere is released to the deep soil, a river and a well. Three identical compartment biosphere submodels (DEEPSOIL, RIVER and WELL) were used in MASCOT to represent the three exposure pathways, each taking as its input the entire flux from the geosphere. The difference between the three submodels was that the inlet was to different compartments appropriate to the three exposure pathways. The compartment structure of the biosphere is shown in Figure 16.5. The outlet from the biosphere was in each case a total dose from concentrations in soil, water (river or irrigation) and seawater.

16.3.3 Results

The total annual individual risks calculated for each biosphere model for the upper and lower repository locations are shown as functions of time in Figure 16.10. It can be seen that for both locations, the deep soil and well biospheres give very similar peak risks (marginally higher in the case of the well), whereas the river biosphere gives risks which are about two orders of magnitude lower.

The risk values, being obtained from mean doses that are estimated from a finite number of realizations (1000 for these runs), are subject to statistical error. From the variance of the observed values, this error can be estimated, and typical 95% confidence intervals are shown in Figure 16.11 (for the lower repository location). For most of the time-range, the upper 95% confidence limit exceeds the best estimate by a factor of about 1.5 or less. This is considered perfectly adequate for a preliminary assessment, with many uncertainties in the data and in the model choices that may well cause biases of rather greater magnitude. The statistical estimation errors could be reduced by including more realizations; to halve the error, four times the number of realizations would be necessary.

16.3.4 Discussion

Risk levels

Using the models and data adopted for these assessment

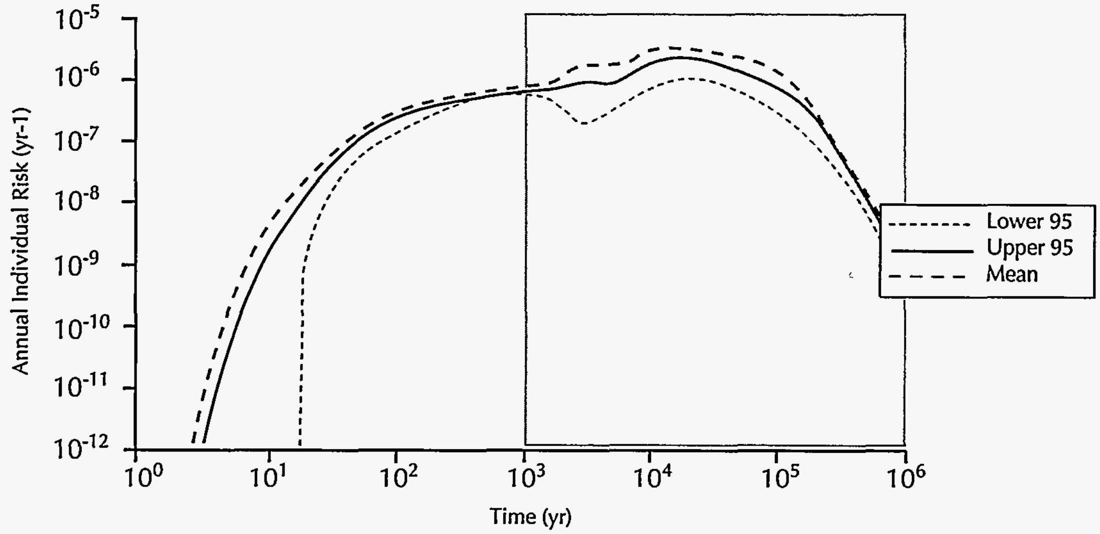


Figure 16.11. Total annual individual risk for release to the deep soil biosphere for the lower repository location plotted against time (with 95% confidence limits).

calculations, it was found, for both choices of repository location and for all the alternative assumptions about the release point to the biosphere, that the predicted risk remained below the target of 10^{-6} yr^{-1} throughout the period of detailed quantitative assessment, up to 1000 years after closure. Beyond this time, no dramatic increases in risk were found, the greatest calculated mean risk being 1.4 10^{-6} between 10^4 and 10^5 years post-closure.

Because of the parameter-value uncertainties, which the probabilistic approach is designed to treat, different sampled realizations of the system gave conditional risks either higher or lower than the mean. From the calculated distributions, it was found that there was a probability of 0.25 to 0.30 of exceeding a risk of 10^{-6} for times up to 10^3 years, and a probability of about 0.50 of exceeding a risk of 10^{-6} for times up to 10^6 years.

Important radionuclides

Up to 1000 years after closure, only ^{129}I makes a significant contribution to risk, other radionuclides either being effectively contained, or else delayed in their passage through the geosphere. Beyond the 1000-year period, the only significant additional contributor to risk was found to be ^{59}Ni.

Effects of the alternative biosphere models

The risk curve for ^{129}I when using the biosphere model in which discharge to the deep soil is assumed, shows a substantially greater initial delay relative to that found using the river or well biosphere models. This suggests that the transport process (when present) from the deep soil to the other compartments provides a non-negligible supplement to the geosphere travel times. Apart from this difference, the shapes of the risk versus time curves for the three biosphere models are very similar.

Differences between the upper and lower repository locations

The peak risk for the upper repository location was found to be 9.8 10^{-7} for the deep soil biosphere and is due to ^{59}Ni. The ^{59}Ni curve clearly shows the difference between paths A and B as two separate peaks. For the lower repository location, the peak risk is higher, at 1.4 10^{-6} for the deep soil biosphere. In fact, the travel times are in general longer from the lower repository location. However, in this case the two peaks arising from paths A and B are not so obviously separated. For the lower repository location, the travel times for the total Path A and the total Path B are more comparable than they are for the upper repository location, and the reason that the risk is lower in the case of the upper location is that the larger difference between paths A and B causes more spreading to occur in the geosphere and hence reduces the risk. This interesting result shows that the spreading of arrival of radionuclides at the surface is not just a matter of hydrodynamic dispersion, but can be contributed to by division of the transport between major alternative paths. However, it should be noted that these two calculations provide insufficient evidence to draw general conclusions about the relationship between repository placement and the extent of this type of dispersion.

Effect of parameter uncertainties

Whereas the expected contribution to risk from ^{59}Ni arises from just a small number of realizations that lead to relatively high conditional risks (those in which both the geosphere travel time and retardation of Ni are low), the contribution to risk from ^{129}I arises from a moderate risk in almost all realizations. This shows that the potential contribution to risk from ^{59}Ni could be subject to significant revision as future reductions are achieved in the present uncertainty about hydrogeological conditions and the retardation of Ni in the geosphere.

16.4 SUMMARY OF PROBABILISTIC SAFETY ASSESSMENT

A number of deterministic variant calculations were carried out, to explore the sensitivity of the system performance to several hypothetical changes. The changes addressed were:

a. no backfill in the ILW caverns;
b. concrete backfill in the ILW caverns;
c. high specific discharge at the source;
d. reduced geosphere travel times;
e. combination of (c) and (d); and
f. low near-field sorption coefficients.

These variations were considered relative to a base case defined by giving to each uncertain parameter in the probabilistic calculations its best-estimate value (the mode or median of the PDF).

The main conclusions are summarized here.

a. The overall peak total risk is similar in the deterministic base case to that given by the probabilistic calculations.
b. In the time range 10^2 to 10^4 years, ^{129}I is the dominant contributor to risk, as in the probabilistic calculations.
c. ^{59}Ni hardly contributes at all to risk in the deterministic base case, indicating that its significant contribution to the mean risks arises from realizations with less than average return time of this radionuclide to the biosphere.
d. Removal of the barrier provided by the ILW backfill was found to affect risk significantly; in the case of the ^{129}I contribution, this is mainly due to its effect on the spreading in time of the release to the geosphere, whereas for ^{59}Ni it is associated with the change in travel time affecting the amount of decay.
e. Decreasing the barrier thickness would increase risks, to an extent intermediate between the base case and the variant with zero thickness; increasing the barrier thickness, however, is unlikely to reduce risks significantly relative to the base case.
f. Decreased groundwater travel times in the geosphere leads to a significant increase in risk; in the case of the ^{129}I contribution, this is mainly due to the associated reduction in the spreading in time of the arrival in the biosphere, whereas for ^{59}Ni, the effect is because reduced travel times allow less decay to occur.
g. The variants involving either an increased flux of groundwater through the repository, or changes to near-field chemistry, do not lead to very great increases of risk relative to the base case.

REFERENCES

1. Agg, P. J., et al., P-KAERI 94 Performance and Environmental Assessment of a Radioactive Waste Repository in Korea, NEMAC/AEA Technology, 1995.

2. Park, H. S., et al., A Study on the Requirements for Basic Design of a Repository for Low-Level Radioactive Waste, KAERI-NEMAC/PR-32/93, 1994.

3. Brown, P. L., et al., HARPHRQ: A Geochemical Speciation Program Based on PHREEQE, NSS/R188, UK Nirex, 1991.

4. Cross, J. E., et al., HATCHES - A Thermodynamic Database and Management System, NSS/R212, UK Nirex, 1990.

5. Martin, J. S., et al., User Guide for BIOS-3A, NRPB-M285, NRPB, 1991.

6. Sinclair, J. E., et al., MASCOT and MOP Programs for Probabilistic Safety Assessment, NSS/R336, UK Nirex, 1994.

7 Hartley, L. J., and C. P. Jackson, NAMMU (Release 6.1) User's Guide, AEA-D&R-0472 (Release 6.1), AEA Technology, 1993.

CHAPTER 17

RESEARCH ON RADIOACTIVE WASTE DISPOSAL IN THE NETHERLANDS WITH SPECIAL REFERENCE TO EARTH SCIENTIFIC STUDIES

A.F.B. Wildenborg

Rijks Geologische Dienst, P.O. Box 157, NL-2000 AD Haarlem, The Netherlands

17.1 INTRODUCTION

Investigations for radioactive waste disposal in the Netherlands were carried out within the framework of the OPLA research programme (OPLA is a Dutch acronym for 'Disposal on Land'). The programme intended to explore the disposal options for nuclear waste in the deep subsurface below the Netherlands. Initially, the research focused on rock salt as a host rock.

Massive bodies of rock salt, with a thickness of 200 to 3,000 m, are present in the subsurface of the northern Netherlands. This potential host rock for radioactive waste disposal was deposited in layers about 220 to 250 Ma ago (the Zechstein period) by evaporation of a closed or semi-closed marine basin. After the evaporites were covered by fresh sediments, the layered salt started to flow at several places in the subsurface of the Netherlands. At many locations this resulted in the formation of salt pillows and sometimes, successively in salt diapirs. The tops of the shallowest salt diapirs rose to depths of about 100 m below the surface. The non-disturbed layered salt is situated generally at a depth of several kilometres below the earth's surface.

The OPLA research programme was divided into three phases for purposes of the interim parliamentary decision-taking procedure. At the end of each phase, government and parliament decide on the question of whether a subsequent phase of the programme is to be performed and, if so, what content and scope it should then have.

Execution of the first phase commenced in 1984. This first phase comprised a feasibility study, investigating various disposal methods and salt formation types with reference to safety. For that purpose, desk studies and laboratory investigations were performed on the basis of existing data in the public domain. In many cases, these investigations were carried out in international co-operation, for example in the area of *in situ* investigations. No decisions have been taken as yet regarding the execution of any further phases of the research programme, which will be more site-specific.

The OPLA Committee reported on the first phase of the research programme in mid 1989. A review of the first phase was given by Van Montfrans in the preceding issue (1991) of the present world-wide review. The conclusions of the studies undertaken in that programme amount, in brief, to a statement that safe disposal of radioactive waste in rock salt formations of a nature and scale as very probably occur in the Dutch subsurface is, in principle, feasible. The OPLA Committee also concluded that certain assumptions on which the conclusions were based required further verification to establish their reliability and accuracy. It was furthermore found that the possibility of identifying in concrete terms exactly which salt formations would be most eligible for further investigation on technical grounds was limited by a lack of site-specific data.

At the same time, according to the ILONA Committee (advising on the policy for radioactive waste management in the Netherlands) it was possible and necessary to perform supplementary research in order to reduce the limitations and margins of uncertainty established in a number of respects by the 1989 findings. This view was supported by the results of an international review performed by the European Community (EC) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD). In addition, it was considered important that attention should be given to new developments, such as the retrievability of disposed-of waste.

17.2 CONTENT AND STRUCTURE OF THE SUPPLEMENTARY RESEARCH PROGRAMME

Based on the conclusions and recommendations of the first phase and the results of the EC/NEA review, the OPLA Committee formulated the main themes of a limited programme of supplementary research, "Phase 1A" (OPLA Committee, 1993). The most important themes are:

- Analysis and reduction of bandwidths in the results of Phase 1, particularly in the results of the safety analysis. This task invoked an improvement of the methodology of the Phase 1 safety approach. This approach was expanded into a methodology enabling systematic treatment of disposal risks. This improves the intercomparability of risks, and makes it possible to allow for probabilities of processes and data.
- In addition, careful analysis and further enlargement of the database on the subsurface was required. At the same time, the extension and further validation of the generic computer models applied in Phase 1 were dealt with. New models, describing the long-term geological evolution of the subsurface, were developed as well. The approach outlined above provides a better confirmatory basis for the findings of the safety study, and they may therefore be considered more accurate.
- Classification of salt formations for further investigation. Grouping of the salt formations was carried out on the basis of expected long-term stability and accommodation space for repository designs. This theme will not be discussed further in the present report.

At the same time, the Committee was requested to consider new developments; these are classed as a separate main theme. Two topics were dealt with in this theme, viz. the retrievability of disposed-of radioactive waste and the direct disposal of spent fuel elements.
Further, the Committee strongly advocated participation in international research programmes.

The supplementary programme was performed in the period from mid 1990 to mid 1993. Within the programme about 20 studies were performed in the areas of study of the OPLA research programme. These areas of study had already been considered in Phase 1: safety (the central theme), technical feasibility (mining engineering), geology and geohydrology, rock mechanics and radiation effects. This paper will deal with results of the supplementary programme and in particular will focus on the outcome of the various earth scientific background studies.

17.3 SAFETY ANALYSIS

Progress was made on the following matters:

- risk assessment method; and
- data and models needed for the risk assessment.

17.3.1 Health risk assessment method

In Phase 1, the health risks of disposal were calculated on a deterministic and conservative basis, i.e. choosing circumstances unfavourable for safety and thereby overestimating risks. This approach hampered the inter-comparability of risks for the various disposal concepts in Phase 1. In addition, this method did not allow uncertainties and sensitivities to be treated in an adequate way.

Within the supplementary programme, a method was developed known as PROSA (PRobabilistisch Onderzoek aan de veiligheid van in Steenzout opgeborgen radioactief Afval = Probabilistic study into the safety of radioactive waste disposed of in rock salt), which accounts systematically for the probability of processes and subsurface data (Prij et al., 1993a). As a result, the risks as calculated are better confirmed and are more readily inter-comparable. The systematic treatment of uncertainties was incorporated within PROSA, thereby improving the significance of the sensitivity analysis as compared to Phase 1.

The PROSA method is essentially based on a system developed for the determination and selection of scenarios (possible situations in which radionuclides are released from a repository and can potentially reach the biosphere). The method is based on the internationally accepted multi-barrier system, which comprises three barriers:

- engineered barriers of the repository;
- rock salt around the repository; and
- overburden with aquifers and impermeable strata.

The degree in which this system acts as a barrier is affected by a complex of Features, Events and Processes (FEPs). These FEPs were used to construct scenarios relevant to conditions in the Netherlands. These scenarios can be subdivided into three classes:

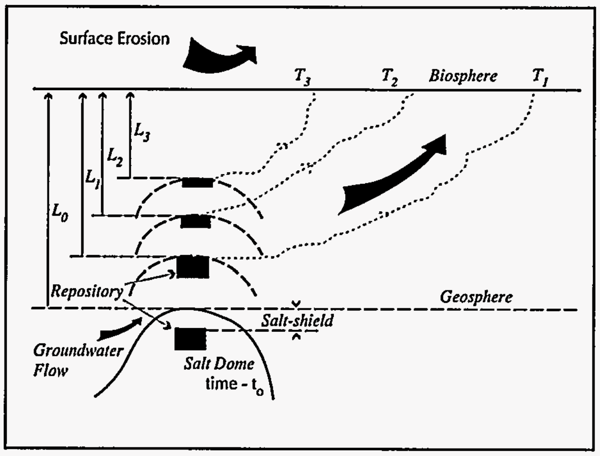


Figure 17.1. Schematic representation of the dissolution/diapirism scenario (Prij et al., 1993a).

- Subrosion/diapirism scenarios belonging to the category of normal evolution scenarios (Fig. 17.1). Gradual ascent of a salt dome (diapirism) brings it into contact with groundwater, salt dissolves (subrosion), radionuclides from the repository enter the groundwater and from there travel into the biosphere.
- Flooding scenarios belonging to the category of altered evolution scenarios. Groundwater penetrates into the repository, for example, as a result of fracturing or a water-permeable inclusion in the rock salt. Radionuclides and salt dissolve in this water. Convergence of the disposal chambers in the salt next forces the brine contaminated with radionuclides out of the salt into the groundwater. The radionuclides then enter the biosphere via the groundwater.
- Human intrusion scenarios belonging to the category of disruptive event scenarios. Various forms of mining engineering activities (exploratory drilling, construction of a mine) may bring future generations into involuntary contact with the waste (see also Prij, 1993).

Due to the lack of sufficient knowledge, two phenomena considered potentially important could not yet be fully calculated with the PROSA method: glaciation (the consequences of an ice age for the repository) and gas formation (consequences for the repository of gas formation near the waste resulting from thermal and radiation effects). Further, only those human intrusion scenarios were recalculated where improved insight relative to Phase 1 made it meaningful to do so.

In the supplementary programme, the risks were calculated for each of the above-mentioned scenario classes and for a number of schematised disposal situations in Dutch rock salt. The assumptions applied are based on the currently available data on the nature and size of rock salt formations as these very probably occur in the Dutch subsurface.

17.3.2 Data and Models Needed for Risk Calculations

Calculating the risk of subsurface disposal requires among other things a comprehensive database relating to the structure and the groundwater system of the subsurface. This database yields the necessary description of the multi-barrier system. For the purpose of the risk calculations, the processes involved in transporting radionuclides through this multi-barrier system are described by means of models.

The database built up in Phase 1 with published data on the subsurface was found to be limited in scale and usefulness. The supplementary desk studies therefore incorporated thorough analysis and enlargement of that geological and geohydrological database. This led to the determination of a number of bandwidths, for example, for spatial geological data on salt formations. In other respects, too, the precision of the data has been improved, for example, on the size of salt formations, rate of diapirism (Fig. 17.2, lower than had to be assumed in 1989), speed of dissolution processes of rock salt in ground water (Fig. 17.3, subrosion), structure and permeability of the rock surrounding the salt, and the mechanical behaviour of salt under the action of temperature effects. In addition, the database was sup-

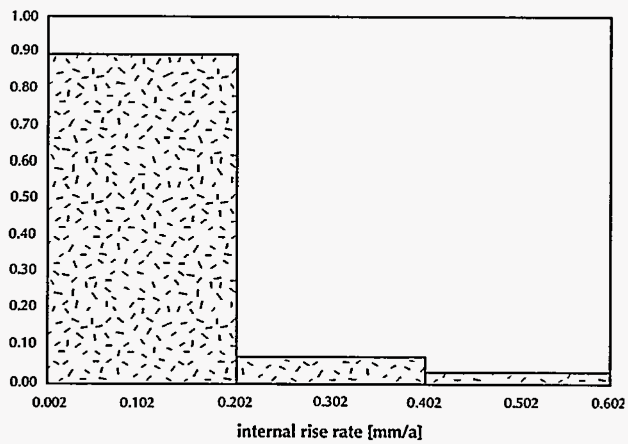


Figure 17.2. Probability density of the average internal rise rate for salt domes in the Netherlands and Germany (Prij et al., 1993a).

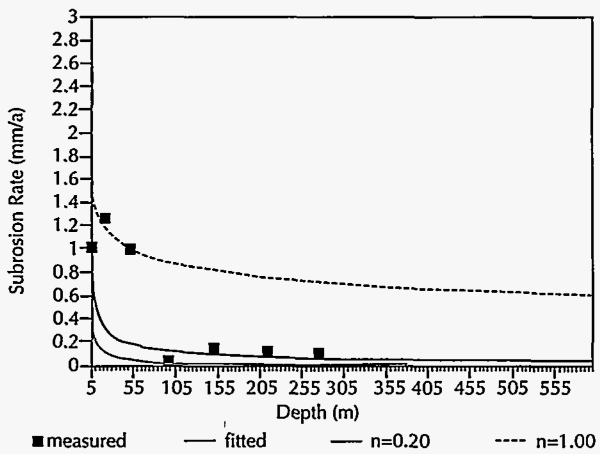


Figure 17.3. Input parameter of the depth-dependent subrosion rate. The measured values have been calculated for salt domes in Germany and the Netherlands with predominantly Quaternary subrosion activity. The upper line corresponds to a power-fit with exponent -0.2 and for the lower line this value is -1.0. The middle line with exponent = 0.64 has been used in the calculations (Prij et al., 1993a).

plemented with data on the subsurface which have become available by the geological mapping of the Netherlands and from geological exploration of the North Sea. This material also made a contribution towards improving the precision of the data.

In Phase 1, three important models were developed and applied for making risk calculations:

- release and transport model for radionuclides from the rock salt;
- transport model for radionuclides in the subsurface; and
- transport and exposure model for the biosphere.

These models underwent limited practical validation in Phase 1. Supplementary research proved the possibility of developing these - essentially generic - models further and validating them against a number of actual practical situations and data. For instance, the model describing the transport of radionuclides in rock salt was further confirmed with results from *in situ* experiments (the Asse Mine in Germany), i.e. under the action of such temperature and pressure as occur in an actual disposal situation. These results indicate that during the initial period of disposal, subsurface spaces in rock salt are closing by convergence more rapidly than was previously assumed. Further validation of this convergence process with reference to more practical data is needed in view of its great impact on safety.

In recent years, the model for radionuclides transport through the subsurface, named METROPOL, has successfully undergone comprehensive international validation in the INTRAVAL project (INternational TRAnsport model VALidation; Leijnse & Hassanizadeh, 1994; Van de Weerd et al., 1994; Van Weert et al., 1994; Leijnse et al., 1996 submitted). Comparison with other models within this project confirmed the reliability of this model. Its applicability to an actual situation was also demonstrated. For conditions prevailing in the Netherlands, this is supported by a case study on the Zuidwending salt dome (Oostrom et al., 1993).

The above-mentioned studies on processes and models and in particular the practical validation of these models have yielded greater clarity on the question of which data are needed for an adequate description of processes such as convergence, diapirism, subrosion and erosion.

17.3.3 Risks of Considered Scenarios

As stated above, by comparison with the approach in Phase 1 the present safety approach has yielded an improved insight into the uncertainties associated with the risks of geological disposal. The risks as now calculated are therefore to be regarded as more precise. Using the PROSA method to calculate the risks of the subrosion/diapirism scenarios yields values smaller than 10^{-9}/year. Similar risk values were found in Phase 1.

For the flooding scenarios, improved insights as compared to Phase 1 allowed modification of the rate of the process whereby subsurface spaces in rock salt are closing (convergence). The resultant radiation doses following dispersal of the radionuclides in the biosphere are found to be very low, and the associated risks much lower than as calculated in Phase 1, namely smaller than 10^{-10}/year.

The above-mentioned model modification for the convergence process in rock salt also has an important influence on the human intrusion scenario further considered (a leaking storage cavern near the repository). The risks now calculated are significantly lower than

Phase 1. For the human intrusion scenarios not analysed in PROSA, the risk appearing from the Phase 1 figures is smaller than 10^{-6}/year. Because large variations can occur in the transport of nuclides in the salt formation, in the overburden and in the biosphere, there is a large spread in the resulting risks calculated. Nevertheless, for all the scenarios considered the disposal risk remains smaller than 10^{-6}/year, and for "natural" scenarios (subrosion, diapirism, flooding) even smaller than 10^{-9}/year.

17.3.4 Risk Determining Features

Certain features of a repository and the geological barrier system around it may be determining for the risk of this particular facility. These features can be identified by determining the influence of all possible FEPs on the risk (sensitivity analysis). Phase 1 showed that the approach then used did not possess sufficient discriminating power to identify risk-determining features of a repository and the multi-barrier system. The principal drawback lay in the conservative approach and the uncertainty as to the extent thereof for each of the disposal situations considered.

Development of the PROSA method made it possible to eliminate this drawback by allowing a systematic approach and introducing the probability aspect. This makes it meaningful to perform a sensitivity analysis to identify risk-determining features of the multi-barrier system. From this sensitivity analysis, it follows that on the basis of the currently available limited database there are two features which predominantly determine the risk of the "natural" scenarios, namely:

- depth of the repository; and
- rate at which this facility is uplifted by possible diapirism.

To summarise, it may be stated that application of the currently available version of the PROSA method to a number of important scenarios and disposal concepts has proved extremely useful. In the first place, this system, as indicated above, provides an improved insight into the risks and uncertainties. Secondly, it helps, for example by means of the risk-determining features, to guide the direction of research in the various sub-areas of the OPLA programme.

17.4 TECHNICAL FEASIBILITY

In Phase 1, two different disposal techniques were studied:

- conventional (dry) mine, and
- deep boreholes drilled from the surface, in combination with caverns.

After study, it was concluded that both techniques are, in principle, technically feasible for salt formations in the Netherlands.

For the mine concept, the supplementary research programme provided further confirmation for that conclusion with the following findings:

- In co-operation with Germany, the practical feasibility has been demonstrated of a mine provided with deep boreholes, dry-drilled from a gallery to a depth of several hundred metres. These boreholes, intended for disposal of canisters with fission waste, constitute an important part of the mine concept.
- Within the same co-operative project, the practical development of a system for lowering, transporting and emplacing radioactive waste canisters in a disposal mine according to the German design has been successfully completed. In addition, the availability of a test facility for *in situ* investigation into rock salt has made a major contribution towards the acquisition of mining engineering experience (the HAW project in the Asse Mine; Prij & Hamilton, 1992; see also section 17.6.1).
- Important advances have been made with regard to technical feasibility, especially relating to the convergence process of rock salt (see section 17.6.1 for further information).
- As a result of the effects of radiation and heat, gas formation and radiation damage can occur in the vicinity of the radioactive waste disposed of in the rock salt. Conclusions regarding the significance of the two phenomena for mine design and disposal safety are still of a preliminary nature (see section 17.6.2 for further information).

With regard to the "deep boreholes from the surface combined with caverns" disposal technique, Phase 1 found that inspection of the reliability of the borehole and cavern seals was an item demanding special attention. In spite of supplementary literature research, no essential progress has been made in this area (Technische Universiteit Delft, 1993b). On the other hand, it has been found that the depth range of this disposal technique exceeds the range found in Phase 1. Depending on the diameter, depths down to around 3000 m are technically feasible with the deep borehole technique.

17.5 EARTH SCIENTIFIC BACKGROUND STUDIES

The major tasks of earth scientific research for radwaste disposal are the description of the present state of the geological barriers (site characterisation) and the prediction of the future state of the geological barriers in support of the scenario analysis.

The supplementary research in the areas of geology and geohydrology consists of two parts:

- improving data and models to support the risk calculations in the safety study (see also section 17.3); and
- increasing the basic knowledge which is needed for proper understanding of important processes in the subsurface. This item includes a number of subjects which emerged as recommendations from Phase 1, and which are not yet immediately applicable in the safety study at this time. Results will be discussed in this section.

17.5.1 Data Quality and Methods of Data Collection

Uncertainty Analysis of Available Geological Data

This research topic deals with the reliability of spatial geological data in general and more specifically with the depth values of geological horizons on contour maps and vertical profiles which are available for the research in the OPLA programme (Wildenborg et al., 1993). An uncertainty analysis of geological data was not carried out during Phase 1 of the OPLA programme.

For this analysis, the following approach was used; various sources of error are responsible for the differences in depth values between observed and real values. Those error sources are introduced by the acquisition of basic data (borehole data and seismic reflection data), by processing and interpretation and also during the construction of derived spatial data like contour maps and vertical profiles. After analysis of the various error sources involved, the magnitudes of the error sources are quantified in standard deviations of the difference between real and observed depth. Assuming mutual independence, all standard deviations of the sources of observation errors could be summed up to obtain insight in the total standard deviation of the observation error :

$$s^2 = \frac{1}{n-1}\sum_n \left(z_w - z_e\right)^2 \qquad (1)$$

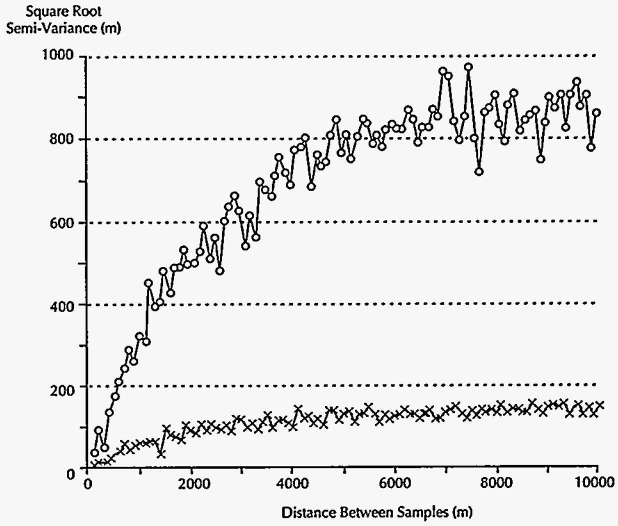


Figure 17.4. Semi-variogram of depth data derived from seismic observations.

where: s = standard deviation, z_w= observed depth, z_e= expected depth, n= number of observations

This analysis was performed on derived spatial data, namely contour maps and vertical profiles (Fig. 17.4).

Borehole data and seismic reflection data are both used as original data for the construction of the spatial data mentioned. Borehole data are highly reliable. The standard deviation of the observation error of the depths to the base of the Tertiary and the top of the Zechstein are estimated to 2 m. Seismic reflection data are less reliable; the standard deviations of the observation errors could be as high as 125 m.

To construct a contour map, interpolation of the original data is necessary. Interpolation by itself is another source of error which increases with increasing distance from data points. The interpolation error also depends on the structural complexity (average dip) of the geological horizon). Using the estimations of the standard deviations of the observation error of borehole and seismic reflection data and the standard deviations of the interpolation error, it was possible to construct maps showing the place-dependent standard deviation of the top of the Zechstein around salt structures, and the base of the Tertiary above the salt.

Methods of Data Collection

Data on the shallow subsurface are available to a reasonable extent when it comes to investigating and modelling important geological and geohydrological processes for use in the safety study. When it comes to data on deeper formations, for example the composition and structure of rock salt and caprock, the rate at which salt dissolves in groundwater, salt concentrations in groundwater, and the diapirism rate of salt formations, they are inadequate.

The OPLA Committee therefore advised that two studies should be commissioned regarding the possibilities for collecting such data. One study concerned the development of equipment for the acquisition of reliable hydrological data at greater depth. An initial practical test has demonstrated the practicality of the technique chosen, and that it is suitable for further development (Fig. 17.5).

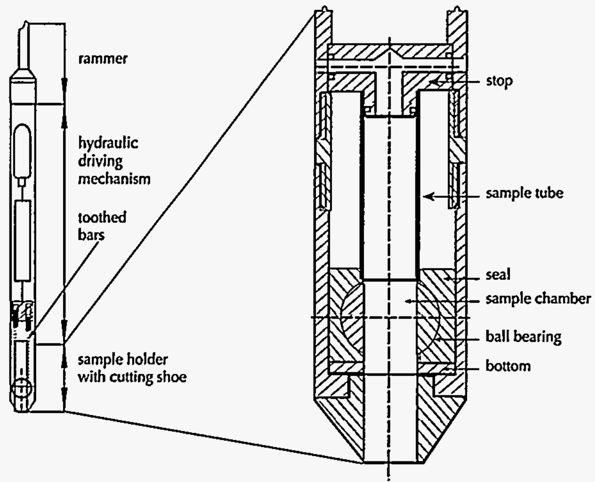


Figure 17.5. Apparatus designed for collecting geochemically undisturbed sediment samples in boreholes (Delft Ground Mechanics, 1993).

Another study was focused among other things on the possibilities of advanced seismic methods in particular for the purpose of high-resolution determination of the depths and size of salt formations and the structure of the overburden (Table 17.1). Here, too, practical tests indicate that progress has been made.

Caprock Properties

Caprock refers to the rock which may be formed at the top of salt formations by the dissolution and removal of rock salt, while poorly soluble constituents remain and newly formed constituents are deposited. Knowledge concerning this rock is important because of the possible effects on mining engineering activities in or near caprock.

A literature study was performed in order to gain further insight into the processes which determine the formation and properties of caprock. That study made it clear that uncertainties still exist about the formation of caprock and the course of the processes relevant to it, and that little is known about the caprock of rock salt formations in the Netherlands. In a general way, it may be stated that it is important to allow for the properties of local caprock when constructing shafts.

A 6 m core section from the lowest part of the caprock was available from the Zuidwending salt dome. Detailed petrographic, geochemical and isotopic analyses were made of this core. The composition of the lowermost part of the caprock evidences a low salinity subroding brine. From the texture of the caprock it could be concluded that fluid flow was predominantly sub-horizontal. The lack of a vertical chemical gradient in the gypsum part of the caprock argues convincingly against any salinity gradient in the water in the caprock. Diffusion processes must therefore be regarded as insignificant.

17.5.2 Prediction of Future State of Geological Barriers

Long-term future predictions of the geological system are of great importance for the risk assessment of radioactive waste disposal. A better understanding of the

Table 17.1. Resolution of various geophysical reconnaissance methods with depth in meters (Meekes et al., 1993).

Depth interval (in m)	Gravity Method	Geo-electrical method	Electromagnetic method	Seismic refraction method	Seismic reflection method
1-50	1-25	1-50	1-50	1-10	no signal
50-100	25-70	15-100	15-100	10-20	3-15
100-300	70-150	30-300	30-300	20-60	4-20
300-500	150-200	100-500	100-500	60-100	5-25

physical and chemical mechanisms of the processes that affect the geological barriers, contributes significantly to a more reliable prognosis of the future state of the subsurface. For rock salt, three processes have been identified that may directly influence the geometry of the rock. These are salt movement, salt dissolution and erosion. Modelling studies have been performed to investigate their relation with the major climatic and geodynamic forces, and their effect on the geological barriers (Wildenborg et al., 1993).

The possible future states of the natural barriers are in general introduced as discrete scenarios in the safety studies. A drawback of this approach is that the total effect of all natural release scenarios is difficult to assess. Geological processes are in varying degree coupled to one another, which makes it difficult or even impossible to split the system in several autonomous compartments. Therefore, it is advisable to pursue an integrated approach parallel or complementary to the scenario method, in which the whole natural barrier system, the processes inclusive, is considered as one entity.

An example of a coupled system is the relation between climatic processes and surface or near-surface processes. Our knowledge of the impact on geologic disposal of recurrent ice ages, induced by climatic changes, has been substantially expanded (Wildenborg et al., 1990). The geological cycles concerned are relatively short, with a length of about 100,000 years, and have almost completely dominated the surface or near-surface processes in Northern Europe for the past one million years. This knowledge, based on comprehensive observations of deposits formed during a number of past cycles, makes it possible to model a large part of these processes in their relevance to the disposal issue. This holds especially for the effects of salt dissolution and erosion on the salt barrier.

Barrier Model

A geological barrier model ideally should simulate the future evolution of the barriers over a period of 10^5 to 10^6 years, should comprise physical and chemical formulations of all relevant processes that directly or indirectly affect the future barrier state and is driven by time-dependent climatic and tectonic forcing mechanisms. Since the beginning of the eighties, various models have been developed to simulate the future behaviour of the geological system in connection with radioactive waste disposal, e.g. GSM and FFSM in the United States, CASTOR in France and TIME4 in Great Britain.
Central in the barrier model to be developed is the local submodel describing the geometry and the properties of the various geological barriers around the disposal facility. The locally operating processes like salt dissolution, salt movement and erosion are incorporated in this part of the model. The climatic and geodynamic boundary conditions are generated in supraregional submodels on the scale of NW Europe or on an even larger scale. Geological observational data have to be gathered in a systematical way to provide input data for the model and data for extensive testing of the model output (Wildenborg et al., 1995).

The mechanisms of the processes that may directly affect the salt barrier (Fig. 17.6), have been studied in detail and will be discussed briefly here.

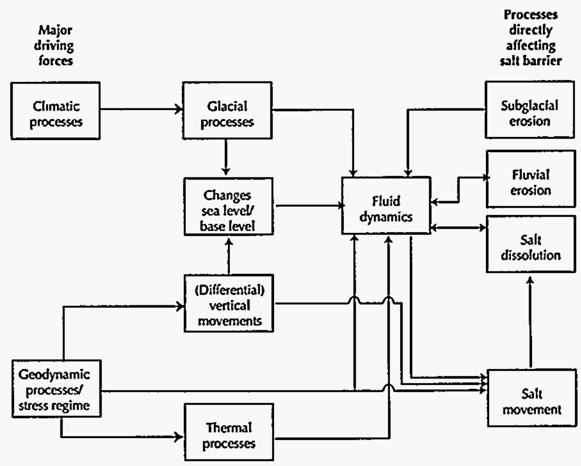


Figure 17.6. Relation diagram of the major processes to be incorporated in the geological barrier model. Note that only part of the pertinent relations between the processes have been marked in this diagram.

Process of Salt Movement

Observations in the Netherlands on- and offshore region show that salt structures are geographically related to faults in the salt basement (Remmelts, 1996; see also Fig. 17.7). The timing of salt movement is related to tectonic phases. For example, the average rise rates of salt structures during the early part of the Oligocene, a period of tensile intra-plate stress, were three to five times higher than during the Late Tertiary and Quaternary, which period was governed by compression.

The role and timing of changes in intra-plate stress also appears on a basin-wide scale. An increased level of compressive stress during the Late Neogene in the North

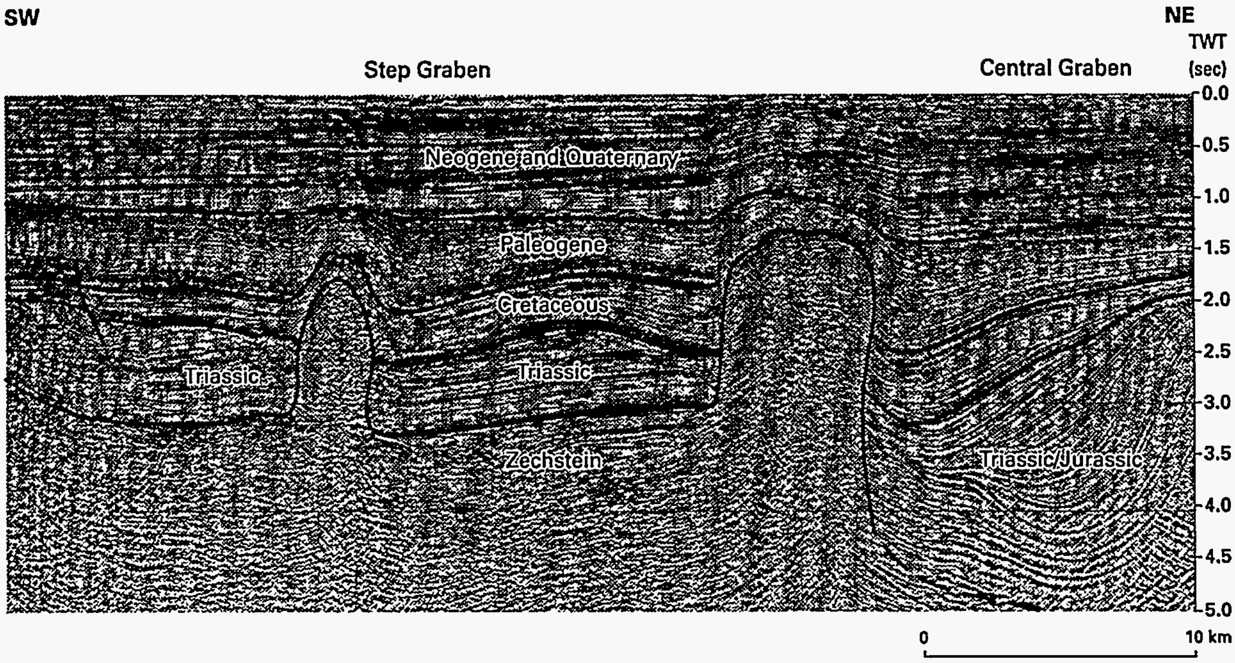


Figure 17.7. Seismic section across salt structures in the offshore region of the Netherlands.

Sea basin is reflected in high subsidence rates. These high rates can not be explained only by the classical lithospheric stretching-cooling model of McKenzie (Cloetingh & Kooi, 1992). Increased rate of uplift during the Late Neogene has been reconstructed for peripheral parts of the North Sea Basin (Van den Berg et al., 1996 submitted). The change in stress level probably is related to important plate-boundary reorganisations. The compressive stress regime is still dominant at present in Northwest Europe (Müller et al., 1992). It is marked by a NW-SE direction, related to the Africa/Europe collision and to ridge-push forces operating in the northern Atlantic.

The effect of intraplate stress on salt movement has been investigated in numerical model studies (Daudré & Cloetingh, 1994). The numerical experiments have been carried out with a two-dimensional planar model of a visco-plastic salt layer and a brittle overburden. Three tectonic scenarios have been investigated: one in which buoyant forces are the only driving mechanism, one in a tensile stress regime and the last with a compressive stress regime (see also Fig. 17.8).

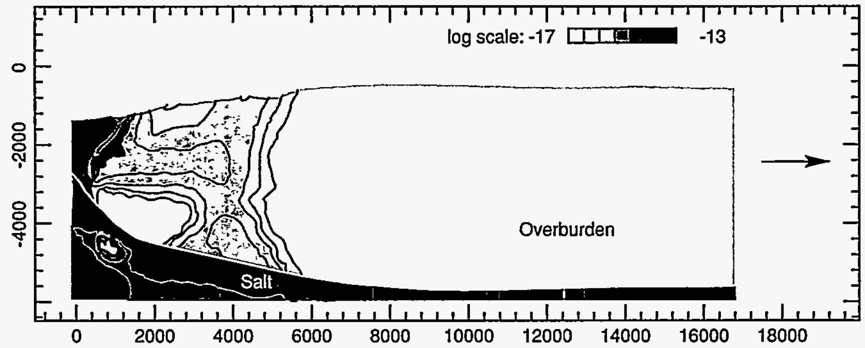
The first modelling experiment has revealed that buoyant forces are too weak to overcome the yield strength of the overburden. Diapiric movement of the salt occurs in a tensional regime with the simultaneous development of shear bands in the overburden. The modelling for a regime of compressional intraplate stress has shown a more modest salt movement and the development of various systems of shear bands.

These results strongly suggest that the classical theory of a gravitational drive for the initiation of salt movement probably does not hold. It appears that regional tectonic forces are a prerequisite for the start of salt movement. The most favourable situation for the initiation of salt movement is a tensional regime; re-activation of diapirism under compression appears to be quite important.

A better understanding of the rheological properties of the overburden is necessary for a more reliable simulation of diapiric deformation. Better understanding of the dynamics of salt diapirism obviously depends on better constraints on the interplay of fluid flow and the initiation of diapirism on a basin-wide scale. Especially, the experiments with compressive stress need further attention, since the fluid pressure in the sedimentary rocks increases significantly in a compressive regime (Van Balen & Cloetingh, 1993). Fluid pressure in rocks is a major factor in determining the rheological properties of the rock. More attention should also be paid to the effect of sedimentation and erosion on the development of salt diapirs (Poliakov et al., 1993).

Process of Salt Dissolution and Climate-Induced Hydrological Changes

The dissolution of salt diapirs is primarily controlled by the amount of available groundwater around the salt



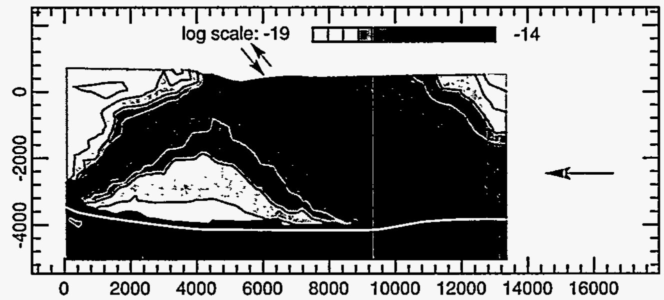


Figure 17.8. Results of mechanical modelling of diapirism. Above: Strain rates after 30 Ma in a tensile regime; strain rates in the range of log(10^{-17} - 10^{-13}/s). Below: Strain rates after 25 Ma in a compressive regime; strain rates in the range of log(10^{-19} - 10^{-14}/s) (Daudré and Cloetingh, 1994).

structure and the solubility and dissolution rates of the evaporite minerals present in the salt dome. In turn, these parameters are controlled by a complex set of other, frequently interrelated parameters such as temperature, pressure, fluid flow composition (i.e. the undersaturation of the groundwater with respect to NaCl), and the permeability of the surrounding sediments. Effects of temperature and pressure on dissolution rates and solubilities are well known from the literature. Subrosion rates as well as solubilities increase with fluid flow velocity and temperature. Since fluid flow velocity is the dominant effect and flow velocities in aquifers in the northeastern Netherlands rapidly decrease with depth, subrosion rates of salt diapirs are expected to decrease rapidly with depth.

The effects of climatic change on groundwater flow and consequently on subrosion at the top of diapiric structures have been investigated and modelled on different scales (Edinburgh University et al., 1996 in prep; Oostrom et al., 1993). Hydrogeological and (palaeo-)environmental data sets have been prepared for application in groundwater flow and subrosion models for:

- the salt-tectonically disturbed subsurface of the north eastern Netherlands for which a regional model and a local model have been developed in a joint project called SESAM in which the Geological Survey of the Netherlands (RGD), the Dutch National Institute of Public Health and Environmental Protection (RIVM) and the TNO Institute of Applied Geoscience participated (see also Fig. 17.9. Van Gijssel, 1995).
- the Cainozoic and Mesozoic subsurface of the Northwest European lowlands, in the scope of an EC-funded, joint project of the University of Edinburgh, RGD, RIVM and the University of Paris-Sud and the Catholique University of Louvain-la-Neuve (Boulton et al., 1993).

Glacial cycles associated with ice sheet expansion and permafrost conditions beyond are believed to have had a major impact on the groundwater flow patterns and hence subrosion rates. In order to approximate this impact, a time-dependent, thermo-mechanically coupled flow line model has been developed in the EC-funded project and applied to a supra-regional transect from South Sweden to northern France, so as to match the

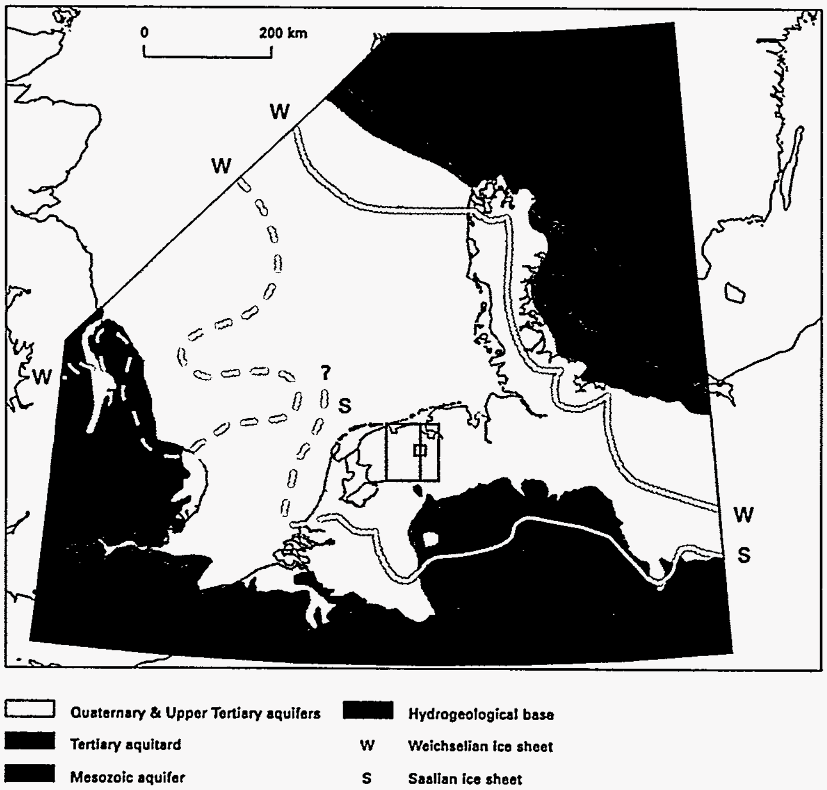


Figure 17.9. Location of the local and regional model areas in the northeastern Netherlands used for the simulation of salt dissolution and the boundaries of the major ice advances in the Late Quaternary. The major part of the Zechstein salt structures in the Netherlands are present within the regional model area.

inferred Weichselian and Saalian glaciations (Boulton & Van Gijssel, 1996). A general subglacial groundwater flow model for NW Europe, consisting of several components and interfaces (an ice-sheet model, a sea-level model, a large-scale groundwater flow model and a subrosion model for rock salt) has been applied to a large number of potential geological situations (Van Weert et al., 1996). The simulations corroborate the importance of the regional hydrogeological conditions and the permafrost distribution beyond the ice sheet margin in controlling ice and groundwater flow.

Drainage and topography have been dramatically changed by the subsequent ice sheet advances. The northward flowing rivers in northwest and central Europe responded by changing their courses in a westerly direction. Lakes that were impounded by glacier ice often drained suddenly, in particular during the deglaciation of the ice sheets and melting of the permafrost. Palaeo-channels formed by abnormally high discharge events are frequently found in the subsurface of the marginal zones of the Pleistocene ice sheets. Deep and penetrative flushing of aquifers by glacial meltwater may have lead to increased subrosion rates of salt diapirs in contact with these aquifers.

The large-scale flow boundary conditions provided by the EC-funded project have been used in the regional and local model simulations for the northeastern Netherlands, carried out in the scope of the SESAM-project, which was focused on one salt diapir only. On the basis of the schematic geometrical frameworks and averaged values of the geohydrological parameters, numerical hydrological models have been reconstructed to evaluate the groundwater flow systems and subrosion rates in the vicinity of selected salt structures in the northeastern Netherlands. The simulations have been concentrated in the first instance on present-day boundary conditions.

In order to investigate the effects of climate change on the groundwater flow patterns, subsequent modelling experiments have been performed using estimated hydrological boundary conditions for relevant time intervals during the Late Quaternary. Regional 3-D groundwater flow simulations on the basis of recon-

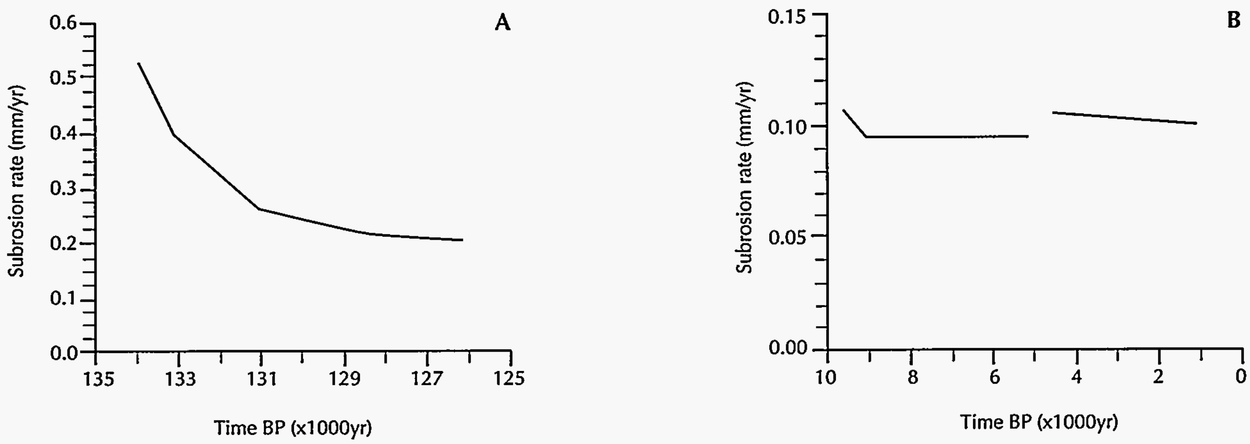


Figure 17.10. Simulated subrosion rates for different time spans. A. Late Saalian ice-free periglacial conditions; B. Interglacial conditions; 2-D simulations, heterogeneous flow field, permeability $k_{65}=10^{-14}$ m^2 (Oostrom et al., 1993).

structed isohypse maps for different post-Saalian, steady-state time intervals in the ice-free area of the northeastern Netherlands clearly indicate the effects of changing climatological conditions on the upper groundwater system (Oostrom et al., 1993). Groundwater flow velocities were a factor two higher in the period following the deglaciation of the Saalian ice sheet as a consequence of large differences in relief and low sea level stands. Subsequent relief levelling and sea level rise during the Eemian interglacial led to low potential gradients and hence resulted in low groundwater flow velocities. Groundwater flow velocities during the Weichselian cold stage with periglacial conditions, were similar to those during the interglacial periods.

Using these regional boundary conditions for a local model, simulating the subrosion rates at the top of a selected salt diapir by the METROPOL-3 code (finite element mesh: Sauter et al., 1990), showed the influence of the magnitude of the groundwater flow velocities near the salt diapir on the subrosion rate. The subrosion rates simulated for the Late Saalian period are found to be substantially higher than for the other periods (Fig. 17.10). Significant differences in subrosion rates between the interglacial periods and the Weichselian time intervals with permafrost conditions, could not be assessed. The input parameters for the sensitivity analyses, such as permeability and anisotropy ratio, show that the resulting range in the simulated groundwater flow velocities and subrosion rates exceed the values calculated for the past.

The subrosion simulations in many ways are simple representations of natural conditions, particularly the 2-D simulations. Since testing of the models used is not possible, because adequate field data and predictions covering thousands of years are lacking, emphasis has been put on calibration for present-day conditions, detailed sensitivity analysis, groundwater flow simulations of past time intervals (which are not necessarily similar to future observations) and comparison of calculated subrosion rates with values known from the literature.

Process of Fluvial Erosion

Fluvial erosion and sedimentation are the results of complex process interactions. Quaternary fluvial dynamics in the Netherlands are mainly governed by the combined effects of sea-level fluctuations, tectonics and climatic change. In addition, and dependent on the space and time scales used, a fluvial system can be controlled by other more local factors and processes (Wildenborg et al., 1993). These complex interactions of processes and factors within the fluvial system were integrated within the model FLUVER (Veldkamp & van Dijke, 1994). FLUVER is a finite-state model using quantitative and qualitative relationships of fluvial systems acting over a long time span (500 ka). Model construction, organisation, operation and testing are extensively described in previous papers (Veldkamp, 1991; 1992). FLUVER simulates the evolution of a fluvial landscape by both sedimentological and erosional processes as controlled by relief, climate, tectonics and fluctuations in base-level of erosion (sea-level changes). The model processes are long-term and large-scale analogies of real erosion and sedimentation processes which react to

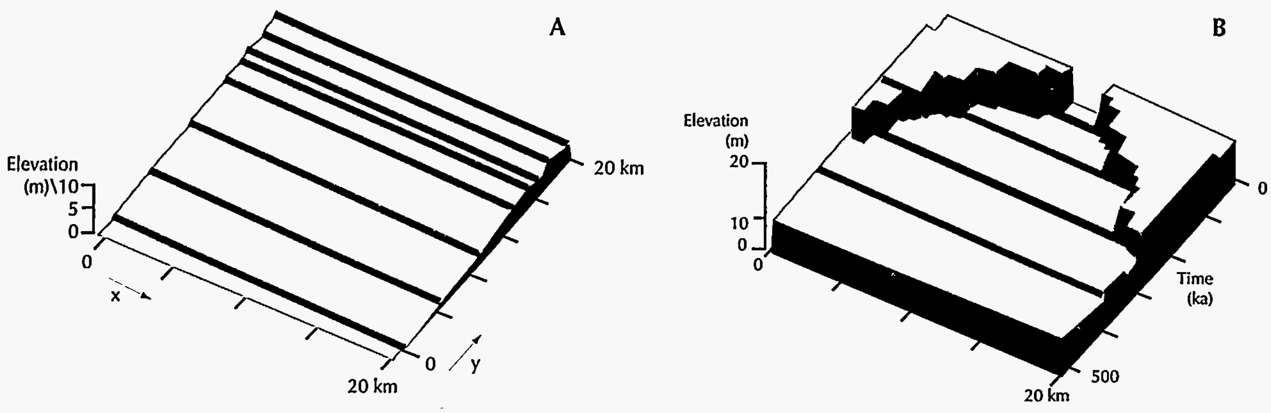


Figure 17.11. Simulation of fluvial landscape in a tectonic subsidence scenario. A - Dynamic evolution of a cross-section through time; B - Landscape after 500 ka.

changes in the climate controlled discharge-sediment load equilibrium which is calculated for time steps of 2 ka each. Both two ka discharge and two ka sediment load are assumed to be a function of climate change as described by the astronomical parameters of Milankovitch theory. Furthermore, both relationships are supposed to be out of phase (Veldkamp, 1991; 1992).

When sediment-input load would exceed the sediment transport capacity, the excess volume will be deposited, and in case the transport capacity exceeds the input load the difference is eroded in the simulated system. The zone with active erosion migrates headward along the longitudinal profile, while the sedimentation zone migrates in a downward direction. Except for changes in climate the simulated fluvial system also reacts to changes in base-level of erosion and vertical crustal movements. In case of uplift or lowering of the base-level of erosion, the fluvial system will strive to compensate by erosion, which is not always possible since climatic conditions may be such that the simulated systems tends to deposition. A similar relationship applies for crustal subsidence and rise of the base-level of erosion which will stimulate sedimentation in the simulated system.

Several simulation runs were made, demonstrating that vertical fluvial erosion in the Netherlands is strongly controlled by sea-level fluctuations and vertical tectonic movements. An example of the simulations with tectonic subsidence is illustrated in Figure 17.11. The tentative conclusion is that during the next few hundred thousand years, fluvial erosion will probably not affect buried salt structures, assuming that climate and change in the base-level of erosion can be satisfactorily described with the Milankovitch theory, tectonic activity in the Netherlands will not change considerably and that no larger fluvial systems than the Rhine or Meuse will enter the Netherlands.

Although reliable long-term input for future conditions is lacking and FLUVER simulations have conceptual validity only, FLUVER can demonstrate potential long-term fluvial erosion effects. To arrive at a more quantitative reliable model, it will be necessary to collect more quantitative data on site-specific fluvial records. Since this model study was mainly based on general data, a comparison and evaluation with actual field data could also improve model performance. Extended and well dated fluvial records of subsiding and uplifting regions like fluvial basin infills and fluvial terraces may serve as a primary data set to which FLUVER or similar models could be tuned. A first tuning exercise was done for the Meuse terraces at Maastricht (Veldkamp & Van den Berg, 1993). As long as extensive testing exercises have not been carried out FLUVER has no reliable quantitative forecasting status.

Process of Subglacial Erosion

From the variety of erosional features related to glacial activity, the formation of very deep tunnel valleys is undoubtedly the most important with respect to the stability of the geological barrier (Wildenborg et al., 1993). Very deep tunnel valleys in northwestern Europe of Elsterian age where analysed on their geometry and possible genesis in order to define tunnel-valley process conditions. Mathematical translation of the formation processes were subsequently used for the construction

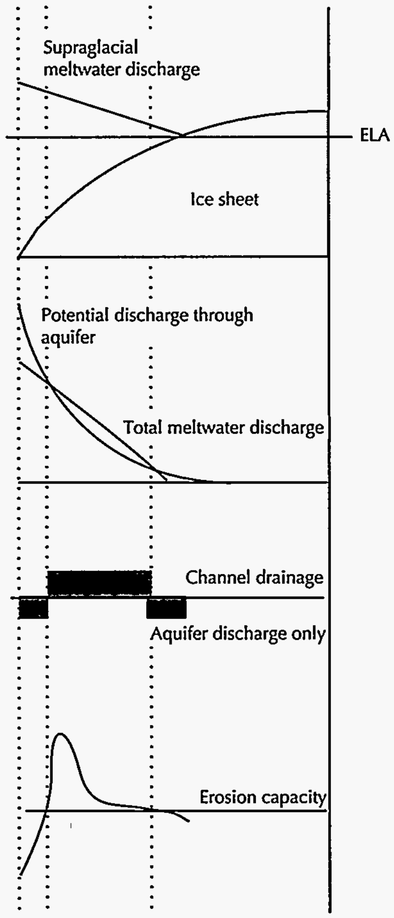


Figure 17.12. Graphical presentation of the conceptual model SUBGLER. ELA = equilibrium line altitude. Below ELA supraglacial meltwater is produced which is assumed to be added to the subglacial meltwater. Drainage through subglacial channels and subsequent erosion occurs if the production of subglacial meltwater is larger than the discharge capacity of the underlying aquifer.

of a computer simulation model (SUBGLER). The aim of the model construction is the prediction of the erosional effects of a future glaciation in the Netherlands.

In accordance with generally accepted theories concerning the development of tunnel valleys, SUBGLER simulates the longitudinal one-dimensional flow of meltwater in subglacial channels under glaciostatic pressure (Nye, 1976; Shoemaker, 1986; Boulton & Hindmarsh, 1987; see also Fig. 17.12). Furthermore, sediment transport functions were developed to relate erosion to the amount of subglacial melt water.

Model construction demonstrated that subglacial channels under a large continental ice sheet overlying an area consisting of a thick sandy aquifer, comparable to the pre-Elsterian conditions in the Netherlands, are only to be expected during the last phase of a glaciation. During this phase, large volumes of supraglacial melt water are assumed to be added to the subglacial system (Jeffery, 1991). The incorporated influence of supraglacial meltwater makes the model sensitive to climatic changes during deglaciation.

Preliminary modelling conclusions after several test runs are based on the individual contribution of various selected input parameters (see also Fig. 17.13). The relative significance of the input parameters are (in decreasing order of importance): mean summer air temperature at the ice sheet margin, longitudinal ice sheet profile, rate of ice sheet margin retreat, and hydraulic conductivity of the aquifer.

The simulations suggest that deep glacial erosion can be expected during any future glaciation, but no reliable estimations can be given on their maximum theoretical depths. In order to allow more precise simulation of future behaviour of subglacial systems, considerable geological field data on Quaternary tunnel valley formation is required. More information is needed on water pressures in subglacial aquifers, sediment loads in subglacial channels and the contribution of supraglacial meltwater to the subglacial system. Current research on the subglacial hydrologic system shows that modelling of groundwater flow within the vicinity of subglacial channels enables a more precise assessment of maximum depths of tunnel valleys (Van Dijke & Veldkamp, 1995).

17.6 Interaction Between Waste and Host Rock

17.6.1 Effects of Changes in Temperature and Stress

The behaviour of rock salt as host rock under the action of temperature and pressure was comprehensively studied in Phase 1, both *in situ* (the Asse Mine) and in the laboratory (Prij et al., 1995). In the supplementary research programme, the study into rock mechanics was concentrated on a continuation of the *in situ* investigations. Results obtained in that context concerning the convergence process of rock salt, which are important for the safety studies, have yielded an increased understanding of this time-dependent process in geological

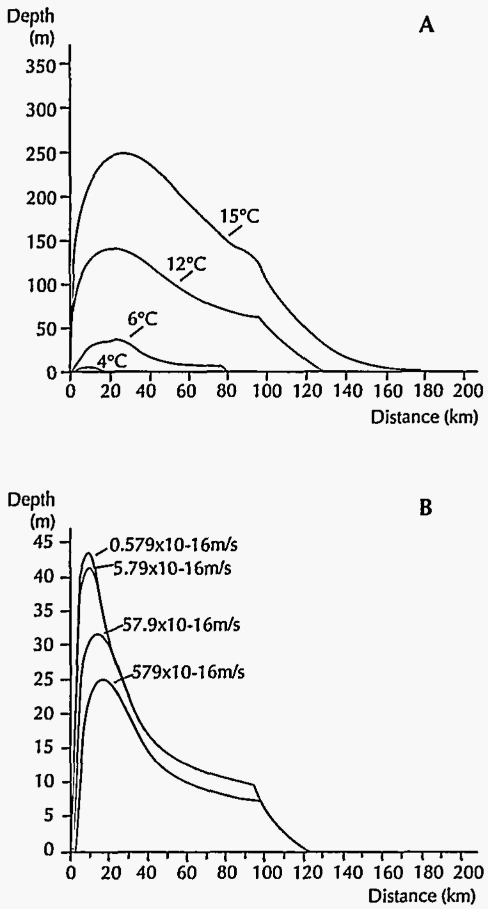


Figure 17.13. Results of the simulations with SUBGLER. A. Effect of changes in air temperature; B. Effect of changes in hydraulic conductivity.

spaces. The convergence process initially proceeds faster than was previously assumed, but after some time it proceeds much more slowly (Fig. 17.14; Prij et al., 1993).

Further modelling of the thermomechanical behaviour of rock salt and practical validation of the models against measurement results have improved the reliability of these models. This made it possible to improve the quality of predictions on the behaviour of a subsurface disposal space under the influence of temperature and pressure. This is important for any modifications and optimisation of repository designs.

The Netherlands Energy Research Centre (ECN) is cooperating with German, French and Spanish research institutes on a number of joint *in situ* projects in the Asse Mine (ECN, 1993b; Prij & Hamilton, 1992; Heijdra & Prij, 1996, in prep). One of those projects, the High Active Waste (HAW) project is a demonstration project

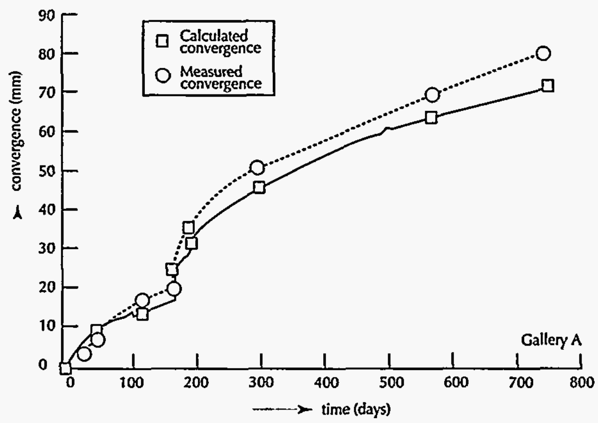


Figure 17.14. Convergence in the mining gallery in the HAW-experiment (Prij et al., 1993b).

for the disposal of high-level radioactive waste. In particular, the interaction between salt and thermogenic waste is being studied here in a practical situation.

17.6.2 Radiation Effects

Disposed-of waste produces radiation. This radiation can cause abnormalities (damage) in the crystalline structure of the rock salt. As a result, energy builds up in the damaged salt, and later it can potentially be released. The results of the Phase 1 research showed that the build-up of radiation damage in salt depends strongly on the presence of certain natural contaminants, such as potassium, bromine, lithium, etc. Uncertainty as to the maximum level of radiation damage under disposal conditions meant that the Phase 1 calculation of the effects of energy release allowed for a damage rate of several tens of percentage points. On the basis of preliminary calculations and assuming a spontaneous and total energy release, these consequences were found to be very limited in scale and did not lead to the release of radionuclides from the salt.

Supplementary laboratory investigation has yielded a number of fresh results (Groote et al., 1991; Seinen et al., 1992; 1995; Garcia Celma et al., 1993). The complexity of this subject matter was such that new questions arose which have not yet been answered. These questions concern the initial stage of the damage, the form and dimensions of the damage nuclei (the colloids) and the influence of such factors as temperature, radiation dose, dose rate, pressure, deformations and natural contaminants (Prij, 1996a, in prep a; Garcia Celma et al., 1995). Insight into these is needed to improve the calculation model that predicts radiation damage under disposal conditions. The foundation for the calculation model was laid by Jain and Lidiard, and in that form it was applied in Phase 1. Progress has been made in the matter of model development, but uncertainties have continued to exist as well, for instance with regard to the causes of the action of contaminants on the damage level.

Laboratory investigations into the properties of strongly irradiated salt (up to radiation doses 6 times higher than under disposal conditions) has shown that, under certain conditions, the damage can rise to around 10%. It has furthermore been found that higher doses are capable of causing even more damage (Rijksuniversiteit Groningen, 1993; Weerkamp et al., 1994).

In some cases, a very rapid reaction was observed, taking an explosive course. Further investigation into the nature of the release process is underway. The significance of this process under disposal conditions merits special attention.

Since Phase 1, good progress has been made with modelling the effects on the surrounding rock salt of the above-mentioned release, capable of allowing for a spontaneous, very rapid and total release of all the energy built-up with radiation damage. The approach taken, which is still subject to scientific debate concerning the release rate and the accompanying temperature rise, broadly confirms the conclusion as drawn in Phase 1 that the effects of sudden energy release would be very limited (ECN, 1993a; Rijksuniversiteit Groningen, 1993; Prij, 1996; Prij, in prep b).

In view of the above, it appears meaningful to continue the investigation into the consequences of radiation damage for disposal safety. For that purpose, the chemical stability of salt and glass, as well as design engineering aspects relating to the repository, can play an important role.

17.7 ALTERNATIVE DISPOSAL CONCEPTS

Current developments in the public interest sphere demanded attention for the following subjects:

- retrievability of disposed-of radioactive waste;
- direct disposal of spent fuel elements.

In an exploratory way, it was examined whether these developments can be integrated in the Phase 1 disposal concepts at the technical level. Their effects, if any, on disposal safety have been considered as far as possible.

17.7.1 Retrievability of Disposed-of Radioactive Waste

Discussions held in wider context and, among other things, an OPLA preliminary study into retrievability disclose a central question: what is envisaged with retrievability? A number of considerations differing widely in nature may be relevant. At any rate, it must be borne in mind that accessibility of disposed-of waste is time-related. Although mining engineering measures make it possible to extend the period of this accessibility to, possibly, some hundreds of years, nevertheless it is impossible to extend it indefinitely. This is because a geological facility is designed for isolation over very long periods, of an order of magnitude of 100,000 years. In that term, of course, retrievability cannot be guaranteed. The question then arises, how is retrievability to be viewed in this context?

All in all, these considerations must be carefully dealt with in a generic study. To that end, an initial step has been taken in carrying out a general EC study, on Dutch initiative, dealing with economics, mining engineering and various host rocks. This study, which is not part of the OPLA programme, is still in progress (Prij & Heijdra, 1995; Heijdra et al., 1996, in prep.).

Quite apart from the above, it is worthwhile considering what mining engineering options are currently available to accomplish a certain measure of retrievability (Technische Universiteit Delft, 1993a; Van den Broek et al., 1994). The investigative OPLA research programme indicates that, in a general sense, retrievability is technically feasible but that this requires the Phase 1 mine concept to be modified in a number of respects. In particular, these modifications include a reduction of the length of the boreholes drilled from the galleries, and a reduction of the thermal effect, in order to keep the waste accessible as easily as possible and for as long as possible. The study also reports that certain concepts for "direct disposal" of spent fuel elements as studied for example in Germany can be readily combined with possible retrievability of the waste. For this purpose, use is made of highly robust "Pollux" containers, which are disposed of in galleries in a mine.

Although the OPLA study is not intended to assess the measure of accessibility for predetermined periods, based on preliminary findings the period refers to a retrievability term of several hundred years, the period during which full information will be present concerning the location of the waste. In the longer term, a situation is envisaged in which the repository has been closed by polydimensional rock pressure and the waste can only be recovered by means of "remining". Underground geophysical survey methods will be able to provide guidance in this case.

The investigative OPLA programme made no statements on the safety aspects of retrievability.

There is no clarity as to the objectives of retrievability. There are a number of possible replies to the question of what is primarily envisaged with retrievability. Different objectives can lead to different mining engineering consequences, each with their own consequences for the "terms of guarantee" and longer-term safety.

17.7.2 Direct Disposal of Spent Fuel Elements

In Phase 1 of the OPLA research programme, it was assumed that, in accordance with the present situation in the Netherlands, spent fuel is reprocessed into re-usable fissile material. The reprocessing waste produced in that process (including the fission waste) form an essential component of the total radioactive waste flow to be disposed of. Developments in the sphere of public interest are calling attention to a fuel cycle without reprocessing. A number of countries (the United States, Sweden) have in the past for various reasons opted for the non-reprocessing route. In such a situation, therefore, it is not processing waste but spent fuel material that has to be disposed of.

The consequences of this for safety and for repository design have for some time been the subject of studies in other countries. For instance, the German Projekt Alternatieve Entsorgung (PAE) investigates two techniques for direct disposal. One technique, which is regarded as the most important, is based on large, thick-wall steel containers in which the entire spent fuel elements are disposed of. These "Pollux" containers are emplaced in galleries in the salt formation, after which the interjacent spaces are backfilled with crushed salt. This method differs essentially from the mine concept with vertical boreholes in the galleries, as studied in OPLA Phase 1. There is greater similarity to the Phase 1 concept in the second method, in which containers filled with short sections of fuel elements are emplaced in boreholes in the galleries.

This study, due for completion in 1995, also considers various design options for the combined disposal of reprocessing waste and spent fuel. This "combined concept" has been subject to exploratory study during the supplementary OPLA research programme (ECN, 1993c). In the disposal concept investigated, the spent fuel originates from a possible enlargement of the nuclear energy potential by 3000 MWe. The reprocessing waste to be disposed of originates from the operations of the existing Dodewaard and Borssele nuclear power stations. As regards technical feasibility, the OPLA study indicates that the chosen disposal technique with boreholes in galleries will not require any drastic modifications to the Phase 1 design. As regards safety, modelling was used to calculate the risk associated with flooding in a disposal mine. It is found that the risk for the technique and waste volume studied here is smaller than 10-6/year.

The exploratory study relating to direct disposal reveals that several feasible disposal techniques are available. The findings of this study match those of the abovementioned PAE study among others.

17.8 CONCLUSIONS

General

On the basis of the results of the supplementary research programme presented above, the OPLA Committee reached the following statements:

- The supplementary research programme disclosed no phenomena or combinations of phenomena which would a priori lead to rejection of the "disposal of radioactive waste in salt formations" option.
- Insight into the parameters affecting the uncertainties in the risks of disposal has increased strongly; as a result, the safety approach is now based on better confirmed data. It has been possible to further validate, analyse and extend the models and data required for the safety calculations. In this way, substantial advances have been made in determining the bandwidths in the results of Phase 1. Accordingly, the objective of the first theme of the supplementary research programme has been achieved.
- Even after completion of the supplementary programme, a number of major uncertainties remain with regard to definition of the risk-determining features of a repository and the natural barriers, practical validation of the models used in the safety study, and the consequences of gas formation and radiation damage in rock salt.
- Development of the PROSA safety method has yielded an extremely useful instrument for scientifically

based risk assessment of geological disposal in rock salt formations. In addition, the PROSA approach appears to have a broader application potential.

- Exploratory study of several new aspects, retrievability of disposed-of radioactive waste and direct disposal of spent fuel in rock salt, has demonstrated that integration of these variants will entail engineering design consequences. The associated design modifications appear to be technically feasible; no prohibitive factors were identified in the study.

Earth Scientific Background Studies

From recent research on model development of geological processes, the following conclusions can be drawn:

- Intraplate stress is the major driving force for the initiation of salt diapirism in the North Sea, which is in contrast with the classical theory of a purely gravitational drive of diapirism.
- Salt dissolution rates in Dutch diapirs are positively correlated with the performance of glacial and subglacial processes.
- Results from the FLUVER model suggest that geological barriers comprising salt diapirs and their cover beds in the Netherlands, have not been, and will not be, affected significantly by fluvial erosion in the past 200,000 years and in the next 100,000 years.
- Although the process of subglacial erosion, having created deep tunnel valleys in the North Sea basin, is still not yet fully understood, the results from SUBGLER model studies suggest that these phenomena were formed during the last phase of deglaciation, as a result of overpressurizing Quaternary aquifers by subglacial meltwater.

Geological studies on the underground disposal of long-lasting hazardous waste in many countries have demonstrated the need for a time-dependent geological simulation model for the geological barriers enveloping the disposal site, in which relevant geological processes are integrated and coupled. Promising results of climatic and tectonophysic research indicate that the development of such a barrier model would be feasible in the next decade. The development of an integrated geological barrier model is only feasible if a large concerted multidisciplinary effort, preferably in an international framework, is carried out.

ACKNOWLEDGEMENTS

The Director of the RGD and the OPLA Committee are thanked for their permission to publish the results in this report. The author acknowledges the institutes which have been co-operating in the SESAM and in the EC-funded projects mentioned above: National Institute of Public Health and Environmental Protection, TNO Institute of Applied Geosciences in Delft, the University of Edinburgh, and the University of Paris-Sud. Mr B.P. Hageman is honoured for editing this report. The help of Mrs A. Garcia Celma and Mr J. Prij (ECN), Mr A. Leijnse (RIVM), W.M.G.T. van den Broek (TUD) and H.W. den Hartog (RUG) in compiling the list of references is greatly appreciated.

REFERENCES

Boulton, G.S. & R.C.A. Hindmarsh, Sediment deformation beneath glaciers: Rheology and geological consequences, J. Geophys. Res., 92 p., 9059-9082, 1987.

Boulton, G.S., A.F.M. Slot, K. Blessing, P. Glasbergen, T. Leijnse and K. van Gijssel, Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences, Quat. Sc. Rev., vol. 12, pp. 739-745, 1993.

Boulton, G.S. and K. van Gijssel, Synthesis of the Saalian and post-Saalian stratigraphy in Northwest and Central Europe: A data-model comparison, Quat. Sci. Rev., (1996, submitted).

Cloetingh, S. & H. Kooi, Intraplate stress and dynamical aspects of rift basins, Tectonophysics, vol. 5, pp. 167-185, 1992.

Daudré, B. & S. Cloetingh. Mechanical modelling of salt diapirism: Influences of the tectonic regime. Tectonophysics, vol. 240, p.59-79, 1994.

Delft Ground Mechanics, Development of a sampling apparatus for the collection of geochemically undisturbed sediment samples at great depth (in Dutch), Report nr. CO-327954/02, 1993.

Den Hartog, H.W., J.C. Groote & J.R.W. Weerkamp, Stored energy in irradiated NaCl - Radiation Effects and Defects in Solids, pp. 133-134, 1995.

ECN, Development and anneal of radiation damage in salt - Phase 1A of the OPLA Programme, Report no. ECN-C-93-086, 1993a.

ECN, In situ experiments in the Asse salt mine, Phase 1A of the OPLA Programme, Report no. ECN-C-93-

069, 1993b.

ECN, Direct disposal of spent fuel, Phase 1A of the OPLA Programme, Report no. ECN-C-93-080; annex: no. ECN-C-93-083 and no. ECN-C-93-099, 1993c

Edinburgh University, RIVM, RGD, Université de Paris Sud und Université de Louvain-la-Neuve, Simulation of the effects of long-term climatic change on groundwater flow and the safety of geological disposal sites, EC Programme on Management and Storage of Radioactive Waste, project no. F12W/0046, (1996, in preparation).

Garcia Celma, A., C. De Las Cuevas, P. Teixidor, L. Miralles and H. Donker, On the possible continuous operation of an intergranular process of radiation damage annealed in rock salt repositories, In: Proceedings of a Symposium on the Geological Disposal of Spent Fuel and High Level and Alpha Bearing Wastes, Antwerp, 19-23 October 1992, IAEA, Proceedings Series: 133-144, 1993.

Garcia Celma, A. and H. Donker, Radiation-induced creep of confined NaCl, In: Radiation Effects and Defects in Solids, vol. 132, p. 223-247, 1994.

Garcia Celma, H. Donker , W.J. Soppe and L. M. Miralles, Development and anneal of radiation damage in salt. CEC, Nuclear Science and Technology Series, EUR 15941 EN, 1995.

Groote, J.C., J.R.W. Weerkamp and H.W. den Hartog, An irradiation facility for radiation damage investigations, Meas. Sci. Technol, vol. 2, pp. 1187-1191, 1991.

Heijdra, J.J., J. Bekkering, J.v.d. Gaag, P.H. v.d Kleyn, and J. Prij, Retrievability of radioactive waste from a deep underground disposal facility, Report EUR 16197 (1996, in preparation).

Heijdra, J.J. and J. Prij, Geomechanical measurements in a deep dry-drilled borehole in Asse II rock salt, EUR 16485 (1996, in preparation).

Jeffery, D.H., Comment on the origin of major incisions, Marine Geology 96, pp. 125-126, 1991.

Leijnse, A. and S.M. Hassanizadeh, Short communication: Model definition and model validation, Advances in Water Resources, vol. 17, pp. 197-200, 1994.

Leijnse, A., H. van de Weerd and S.M. Hassanizadeh, modelling of madionuclide transport in Koongarra, Australia; the effect of a moving weathering zone, Water Resources Research, (1996, submitted).

Meekes, J.A.C., E. Bakker, P.F.M. de Groot, J.M.J. Kuijk, M.H. Mulder and A.F.B. Wildenborg, Geophysical methods for the hydrogeological reconnaissance of salt domes and the adjacent sediments, Phase 1A of the OPLA Programme, Report of IGG-TNO & RGD, no OS 93-15-B, 1993.

Müller, B., M.L. Zoback, K. Fuchs, L. Mastin, S. Gregersen, N. Pavoni, O. Stephansson and C. Lunggren, Regional patterns of stress in Europe, J. Geophys. Res., vol. 97, p. 11783-11803, 1992..

Nye, J.F., Water flow in glaciers: Jökulhlaups, tunnels and veins, J. Glaciology, Vol. 17, No. 76, pp. 181-207, 1976.

Oostrom, M., K. van Gijssel and W. Zijl, Modelling subrosion and groundwater flow in the vici-nity of the Zuidwending diapir on the basis of geometrical and (palaeo-)hydrological boundary conditions for the north eastern Netherlands, The SESAM-project in the OPLA Programme, Phase 1A, RIVM-Report 715205004, 1993.

OPLA Committee, Research into geological disposal of radioactive waste in the Netherlands, Final Report on Phase 1 of the OPLA Programme, Ministry of Economic Affairs, 1989.

OPLA Committee, Research programme on geological disposal of radioactive waste in the Netherlands, Final report Supplementary Research Programme, Phase 1A, 1993.

Poliakov, A., R.T. van Balen, Y. Podlachikov, B. Daudré, S. Cloetingh and C. Talbot. Erosion and diapirism: A comparative analysis of salt diapirism for different cases of erosion, Tectonophysics, vol. 226, pp. 199-216, 1993.

Prij, J.. The role of human intrusion in a waste repository in rock salt, International Conference Safewaste 93, organised by SFEN, French Nuclear Energy Society, Avignon 13-18/06/1993, Proceedings, vol. 2, pp. 490-501, 1993.

Prij, J., Myth or nightmare: Safety consequences of the release of radiation induced stored energy, Nuclear

Technology, January, 1996.

Prij, J., Radioactive waste repository relevant parameters, In: Radiation damage in salt, EUR, (1996a in preparation,).

Prij, J., Evaluation of the safety consequences of radiation induced stored energy in a repository in rock salt, In: Radiation damage in salt, EUR, (1996b in preparation).

Prij, J., B.M. Blok, G.M.H. Laheij, W. van Rheenen, W. Slagter, G.J.M. Uffink, P. Uijt de Haag, A.F.B. Wildenborg and D.A. Zanstra, PRObabilistic Safety Assessment, Final report, of ECN, RIVM and RGD in Phase 1A of the OPLA Programme, 1993a.

Prij, J., V. Graefe, T. Rothfuchs, and L.H. Vons. Modelling of the thermo-mechanical behaviour of solid rock salt and crushed salt, CEC Workshop on THM properties, report EUR 16219 en. 1995.

Prij, J. and L.F.M. Hamilton. Thermo-mechanical analyses of the HAW testfield, Nuclear Engineering and Design vol. 138, pp. 203-215, 1992.

Prij, J., and J.J. Heijdra, Feasibility and economic consequences of retrievable storage of radioactive waste in the deep underground, Global, vol. 2, pp. 1770-1777, 1995.

Prij, J., J.J. Heijdra, and B. van den Horn. Convergence and compaction of backfilled openings in rock salt, 3rd Conference on the Mechanical Behaviour of Salt, September 1993b.

Remmelts, G., Salt tectonics in the southern North Sea, the Netherlands, KNGMG Special Publication: Geology of gas and oil under the Netherlands, 1996.

Rijksuniversteit Groningen, Radiation damage in NaCl - Report in Phase 1A of the OPLA Programme, 1993.

Sauter, F.J., S.M. Hassanizadeh, A. Leijnse, P. Glasbergen and A.F.M. Slot. METROPOL, A computer code for the simulation of transport of contaminants with groundwater, RIVM-report 725205002, 1990.

Seinen, J., J.C. Groote, J.R.W. Weerkamp and H.W. den Hartog, Radiation damage in NaCl: General model of nucleation and aggregation processes in doped NaC, Radiation Effects and Defects in Solids, vol. 124, pp. 325-339, 1992.

Seinen,J., D.I. Vainshtein, H.C. Datema, and H.W. den Hartog, Radiation Damage in NaCl: the annealing behaviour of heavily damaged KBF4 doped crystal, J. Phys.: Condensed Matter, vol. 7, pp. 705-716, 1995.

Shoemaker, E.M., Subglacial hydrology for an ice sheet resting on a deformable aquifer. J. Glaciology, vol. 32, no. 110, pp. 20-29, 1986.

Technische Universiteit Delft, Retrievability of radioactive waste, Phase 1A of the OPLA Programme, report no. 54595, 1993a.

Technische Universiteit Delft, Aspects of the deep boreholes/cavity option, Phase 1A of the OPLA Programme, report no. 52610, 1993b.

Van Balen, R.T. and S. Cloetingh, Intraplate stresses and fluid flow in extensional basins, In: A. Horbury & A. Robinson (eds). Diagenesis and basin development. AAPG Studies in Geology, vol. 34, p. 87-98, 1993.

Van den Berg, M.W., W. Groenewoud, G.K. Lorenz, P.J. Lubbers, D.J. Brus and S.B. Kroonenberg, Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley Rift System, Geologie en Mijnbouw, Special Issue Roermond earthquake, (1996, submitted).

Van den Broek, W.M.G.T., M.J.V. Menken and H.C. Heilbron, Preliminary study on retrieval of radioactive waste from a salt-mine repository, Proc. Symp Waste Man., Tucson (Arizona), March 1994, vol. 1, pp. 593-596,1994.

Van de Weerd, H., A. Leijnse, S.M. Hassanizadeh and M.A. Richardson-Van der Poel, INTRAVAL Phase 2, Alligator Rivers Natural Analogue: Modelling of uranium transport in the weathered zone at Koongarra (Australia), Report no. 715206005 RIVM, 1994.

Van Dijke, J.J. and A. Veldkamp, Climate-controlled glacial erosion in the unconsolidated sediments of north western Europe, based on a genetic model for tunnel valley formation, Earth Surface Processes and Landforms, vol. 20, 1995.

Van Gijssel, K., Hydrogeological and palaeoenvironmental data input for hydrological model simulations in the north eastern Netherlands, Meded. RGD, vol. 52, 1995.

Van Montfrans, H.M.. Research Program on geological disposal of radioactive waste in The Netherlands -In: Geological Problems in Radioactive Waste Isolation, Proc. Workshop W3B, 28th IGC, Washington, D.C., July 1989, pp. 103-114, 1991.

Van Weert, F.H.A., A. Leijnse and S.M. Hassanizadeh. , INTRAVAL Phase 2, Gorleben Test Case, Report no. 715206004 RIVM, 1994.

Van Weert, F.H.A., K. van Gijssel, A. Leijnse and G.S. Boulton, The effects of Pleistocene glaciations on the geohydrological system of Northwest Europe, J. Hydrology, (1996, submitted).

Veldkamp, A., Quaternary river terrace formation in the Allier basin, France, A reconstruction based on sand bulk geochemistry and 3-D modelling, Doctoral thesis Agricultural University Wageningen, 172 pp, 1991.

Veldkamp. A., A 3-D model of fluvial terrace development in the Allier basin (Limagne. France), Earth Surface Processes and Landforms, vol. 17, pp. 487-500, 1992.

Veldkamp, A. and M.W. van den Berg, Three-dimensional modelling of Quaternary fluvial dynamics in a climo-tectonic dependent system, A case study of the Maas record (Maastricht, The Netherlands) Global and Planetary Change, 8: pp. 203-218, 1993.

Veldkamp, A and J.J. van Dijke, Modelling of potential effects of long term fluvial dynamics on possible geological storage facilities of nuclear waste in the Netherlands, Geologie en Mijnbouw, vol. 72, pp. 237-249, 1994.

Weerkamp, J.R.W., J.C. Groote, J. Seinen, and H.W. den Hartog. Radiation Damage in NaCl, Part I to IV, Phys. Rev., vol. B50, pp. 9781-9802, 1994.

Wildenborg, A.F.B., J.H.A. Bosch, E.F.J. de Mulder, R. Hillen, F. Schokking and K. van Gijssel, A review: effects of (peri-)glacial processes on the stability of rock salt - Proc. 6th Int. Congr. Int. Ass. Eng. Geol., 5, pp. 2763-2770, Amsterdam, Balkema, 1990.

Wildenborg, A.F.B., M.C. Geluk, Th.A.M. de Groot, G. Remmelts, G.Th. Klaver, A.N.M. Obdam, A. Ruizendaal and P.J.T. Steins, Evaluation of salt bodies and their overburden in the Netherlands for the disposal of radioactive waste, Rijks Geologische Dienst, vol. a. Spatial data, vol. b. Salt movement, vol. c. Caprock formation and subrosion vol. d. Fluvial and subglacial erosion, vol. e Geological barrier model, Project GEO-1A in the OPLA Programme, Phase 1A, report 30012/ER, 1993.

Wildenborg, A.F.B., S.A.P.L. Cloetingh, E.F.J. de Mulder, R.T. van Balen, J.J. van Dijke, K. van Gijssel, A. Veldkamp, B. Daudré and G. Remmelts. Towards a predictive barrier model for Zechstein rock salt in the Netherlands, Colloque Géoprospective, April 1994, Paris, 1995.