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Geological Problems in Radioactive Waste Isolation

A WORLD WIDE REVIEW

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Acknowledgements

This work was supported in part through U. S. Department of Energy Contract No. DE AC03-76SF00098. The schematic drawing on the cover is for the low level and intermediate level waste repository that is now being constructed at Olkiluoto, Finland. We wish to thank Dr. Veija Ryhänen of Teollisuuden Voima Oy for his kind permission to use this drawing. The very careful work of Ms. Ellen Klahn in typing and formatting this report is gratefully acknowledged. The excellent work on the graphics by Mr. William Bero is also gratefully acknowledged.

Chapter 1

1. Introduction

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The problem of isolating radioactive wastes from the biosphere presents specialists in the fields of earth sciences with some of the most complicated problems they have ever encountered. This is especially true for high level waste (HLW) which must be isolated in the underground and away from the biosphere for thousands of years. The most widely accepted method of doing this is to seal the radioactive materials in metal cannisters that are enclosed by a protective sheath and placed underground in a repository that has been carefully constructed in an appropriate rock formation.

The HLW problem is complicated because of the heat generated during the decay process. If the HLW is not stored at the surface for a lengthy period of time so as to lose much of its thermal generating capacity, the heat released in the underground can raise the temperature of the repository over a long period of time with a maximum increase of as much as 200° C. The projected size of a repository involves a rock volume on the order of a cubic kilometer, and to predict the effects of significantly raising the temperature of the rock by this amount involves a number of complicated questions. To simplify this problem, several countries have decided to store their HLW at the surface for 40 to 50 years to dissipate the generated heat and minimize the temperature increases in the underground repository.

The first investigations on storing radioactive waste underground were started in United States in the early 1960's in a salt mine near Lyons, Kansas and in West Germany in 1965 using an underground laboratory in the Asse salt mine. The early work at Asse was concerned mainly with various disposal techniques for isolating low level and medium level radioactive wastes in rock salt. Later investigations concentrated on problems concerned with high level waste (Langer et al., 1990). The first effort to study the problems of isolating HLW in granitic rock was initiated in late Spring 1977, when another underground laboratory was set up in an abandoned iron ore mine at Stripa, Sweden. This program was accomplished as part of a Swedish-American cooperative program that was initiated by a bilateral agreement between the U. S. Energy Research and Development Administration (now the U.S. Department of Energy) and the Swedish Nuclear Fuel Supply Company (Witherspoon and Degerman, 1978). The program was later expanded into the International Stripa Project that is still operating today.

Essentially every country that is generating electricity in nuclear power plants is faced with the problem of isolating the radioactive wastes that are produced. The general consensus is that this can be accomplished by selecting an appropriate geologic setting and carefully designing the rock repository. Much new technology is being developed to solve the problems that have been raised and there is a continuing need to publish the results of new developments for the benefit of all concerned.

The 28th International Geological Congress that was held July 9-19, 1989 in Washington, D. C. provided an opportunity for earth scientists to gather for detailed discussions on these problems. Workshop W3B on the subject, "Geological Problems in Radioactive Waste Isolation - A World Wide Review" was organized by Paul A. Witherspoon and Ghislain deMarsily and convened July 15-16, 1989. A copy of the program is given in the Appendix. Fifty eight persons were in attendance from the following 16 countries:

Belgium
Canada
China
France
E. Germany
W. Germany
Italy
Japan
The Netherlands
Soviet Union
Spain
Sweden
Switzerland
Taiwan
United Kingdom
United States

Reports from 15 of these countries have been gathered for this publication. Contacts were also made with workers in Argentina, Finland, India, and Yugoslavia and this has produced reports from four additional countries.

Representatives from the U.S. Nuclear Regulatory Commission, the OECD Nuclear Energy Agency, the Commission of the European Communities and the International Atomic Energy Agency were also invited to participate in the workshop. Reports from each of these agencies are included to provide a description of their national and international activities.

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Chapter 2

Argentine Project for the Final Disposal of High-Level Radioactive Waste

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2.1. Introduction

Since 1980, Argentina has been carrying out a research program on the final disposal of high-level radioactive waste. The quantity of wastes in the next century will be significant. It was decided to start the studies well in advance in order to demonstrate that such wastes can be disposed of in a safe way.

The option of direct disposal of spent fuel elements was discarded, not only because of the energy value of the plutonium, but also for ecological reasons. The presence of the total quantity of actinides in the unprocessed fuel elements would imply a more significant radiological impact that that caused by recycling the plutonium to produce energy.

The decision to solve the technical issues connected with the elimination of the high-level wastes well in advance was also made to avoid transfering the problem to future generations. This decision was based not only on the technical problems but also on issues of ethics.

2.2. Waste Disposal

The basic assumption in disposing of radioactive wastes is to keep them isolated from the biosphere for a period of time sufficient for the necessary decay in radioactivity. The disposal of high-level radioactive wastes in an appropriate solid form in deep geological formations is a solution that brings risks to both present and future generations. These risks will not be any higher than those usually accepted in everyday life.

Previous evaluations have shown that the disposal of wastes in crystalline rocks at a depth of 500 m or more should reduce the overall radiological impact sufficiently. Therefore, after taking the geological features of the country into account, a decision was made to carry out the waste disposal operation in stable granitic systems at a depth of 500 m, away from seismic areas and in formations with very low hydraulic conductivity.

2.3. Siting Studies

Studies to select a site started in 1980. The first step consisted of an analysis of all granitic outcrops that were know in the literature. Both petrographic and structural features for each outcrop were surveyed, as well as the dimensions and thicknesses of the rock bodies. The seismic and hydrogeological features of each area and the potential for mining and petroleum exploration were also considered. As a result, 198 granitic sites were identified, spread all over the country (Figure 2.1).

As a second step, it was necessary to discard certain sites on the basis of the following criteria: (a) sites located within areas of high seismicity, (b) sites located in areas with present, or the potential for future, mining or petroleum exploitation operations, (c) petrographic features in the rocks indicating important alterations, such as excessive erosion or advanced decomposition, and (d) sites located in areas with know unfavorable hydrogeological characteristics. This process led to the selection of seven granitic sites in the Provinces of Chubut and Rio Negro, in the southern part of Argentina.

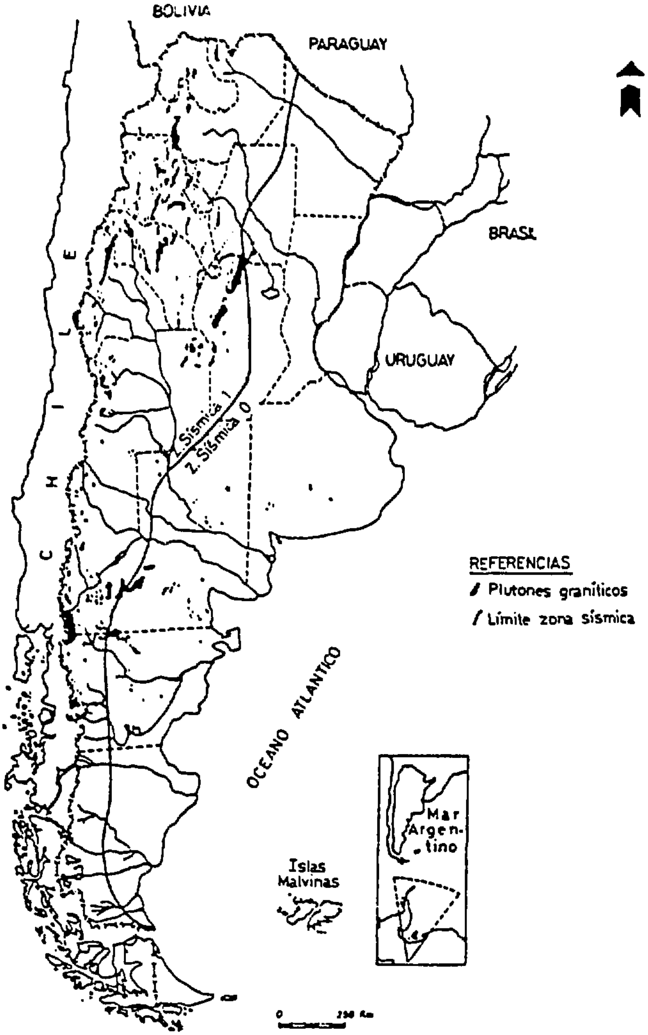

Figure 2.1. Location of granitic sites

A third step was based on a survey of the selected granitic sites and led to the idenucation of four specific outcrop areas that were appropriate for further detailed studies: La Esparanza and Chasico in the Province of Rio Negro and Calcatapul and Sierra del Medio in the Province of Chubut. The locations of these four sites are shown on Figure 2.2. The decision was made to carry out detailed studies at Sierra del Medio, as per the following scheme: (a) photinterpretation, (b) statistical analysis of alignments, (c) geological and geophysical review of rock formations, (d) drilling to an intermediate depth of 200 m, (e) geomorphological and hydrogeological analysis of the area, and (f) deep drilling to a depth of 800 m.

As an aid to the photogeological survey, detailed research work was performed on the petrographic composition of the granitic formations along a series of transverse profiles with field sampling of the significant facies. These samples were analyzed macroscopically and microscopically to determine the rock variations over the site. Simultaneously, a preliminary geophysical survey was carried out with the objective of analyzing conditions around the border of the granitic body and the eventual development of the structure that is now linked to the intrusion of the present rock mass. The profiles were surveyed by seismic and geoelectric methods.

On the basis of the analysis of lineations and the results from the geological and geophysical surveys at Sierra del Medio, ten locations were made for the drilling of wells for petrographic and structural research work. These wells ranged in depth from 200 m to 280 m and provided subsurface information on the boundaries of the selected area, as well as data on fractures, dikes and other surface abnormalities at depth. The data obtained were analyzed by means of geostatistical techniques.

Later, four wells with a diameter of 45-76 mm were drilled down to a depth of 800 m. The purpose was to study the petrographic characteristics of the deeper rocks and the potential behavior of the deep groundwaters.

Geological studies were also made of the volcanic deposits located in the Gastre graben about 60 km from Sierra del Medio. These investigations were aimed at determining the past influence of volcanic emanations on the stability of Sierra del Medio. The results established the fact that the basaltic lava flows have not produced alterations at Sierra del Medio and that the ages of these flows, determined by K-Ar methods, are older than eight hundred thousand years, reaching in some cases up to three million years. These results are consistent with dates obtained using paleomagnetic techniques.

In the near future, a detailed hydrogeologic investigation at a depth of 500 m or more will be started, with the aim of determining the hydraulic conductivity of the formations and the physicochemical properties of the deep groundwaters. The measurement of hydraulic conductivities and the sampling to determine the amount of water present in the deep formations will be performed using special equipment developed in Argentina. This equipment permits one to make insitu measurements of hydraulic conductivity, pH values, redox potentials and conductivity, as well as to collect water samples for physico-chemical analyses and age dating.

2.4. Engineered Barriers

The radioactive wastes will be incorporated into a glass matrix of the borosilicate type and enclosed within a stainless steel container. This waste container will be clad with a 10-cm thick wall of lead that is protected on the outside by a metal cover, as shown in Figure 2.3. The content of fission products and transuranic oxides in the glass matrix is limited to 10% by weight. The minimum decay time of the waste before being placed underground in the repository is limited to 20 years. The thermal load created by each container will be 500 w.

An additional engineering barrier will be provided by the final sealing of the repository holes with a buffer material that offers great resistance to water movement as well as radionuclide migration. This will be attained with a material composed of sand and bentonite.

2.5. Basic Engineering Design

The repository shall satisfy the needs of six nuclear power plants operating over a 30-year period with a total installed power rating of 3.4 GWe. The wastes resulting from the reprocessing of spent fuel elements and the subsequent vitrification will require approximately 3000 containers of the design shown in Figure 2.3. Also, further expansion of the repository in the future must be forseen as the needs of nuclear power program in Argentina increase.

A basic engineering design was carried out for the purpose of determining the feasibility of the project and obtaining a first estimate of repository costs. This project included the conceptual design of the repository at a depth of 500 m, the accessing facilities, the transfer equipment for the containers and buffer material, and other equipment and personnel.

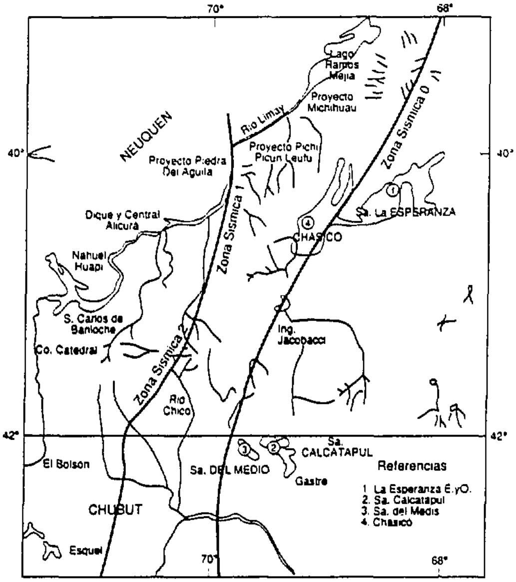

Figure 2.2. Locations of the selected granitic sites.

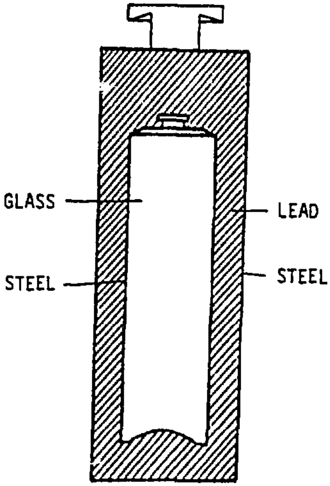

Figure 2.3. Conceptual design of waste container.

In order to guarantee the performance properties of the granite and buffer material, the maximum design temperature in the rock was set at 60°C. Studies of the evolution over time of the temperature field within the granitic rock show that the 60-degree limit requires a separation between containers of 5 m and a thermal power density in the horizontal plane of the repository of 5 W/m^2. The containers will be stored in a vertical position in holes drilled in the floor of the galleries and spaced at 20-meter intervals. The holes will have a diameter of 1 m and a depth of 4.5 m.

Three alternatives for accessing the repository were analyzed: (a) vertical shafts, (b) inclined drifts, and (c) a combination of these excavations. The design of the access excavations and galleries and the order for proceeding with the mining of the various openings were analyzed from the technical and economical points of view as well as from resulting stress conditions induced in the rock formation. Figure 2.4 shows a schematic view of one of the layouts for the repository.

2.6. Transportation

The waste containers will be transported to the repository in trucks, at the maximum rate of 180 per year. Design of the containers will be accomplished in accordance with the requirements of the Regulation for the Saftey Transportation of Radioactive Materials of the International Atomic Energy Agency. They will be unloaded into a temporary storage area where they will be kept until the time of final disposal. Transfer of the containers to the isolation holes in the galleries will be made using a specially constructed transport module as is shown schematically in Figure 2.5. Transportation of containers to the repository location should be carried out without special restrictions. Transportation by rail or a mixture of truck and rail are considered as alternatives.

2.7. Repository Cost

The estimated cost of a repository with this design is about $350 million which includes the costs of engineering, construction, operation and final closure of the site. This represents 1.5% of the cost of a KWh.

2.8. Radiological Impact

Management of high level radioactive wastes, like other steps in the fuel cycle, is carried out taking into account the radiological safety criteria, as applied to Argentina, that are consistent with international recommendations. The basic criteria are to avoid the occurence of non-stochastic effects, to limit the probability of the occurence of stochastic effects, and to reduce the long term collective detrimental effects as far as is reasonably achievable.

Non-stochastic effects will be avoided by designing the container in order to keep the wastes totally isolated for the first 1000 years, which provides enough time for the fission products to decay sufficiently. This should be achieved by cladding the wastes with a cover of 10 cm of lead. In order to reduce the risk to individuals to a sufficiently low level, the wastes will be incorporated into a glass matrix of the borosilicate type with a very low leaching rate. This will produce delay times of 10,000 years or more.

Once the isolation period provided by the engineered barriers ends, the container will be corroded by water, and the radionuclides will be subject to leaching with a consequent migration to the biosphere. Transportation by deep groundwater is the only media by which the radionuclides involved can return to the environment. This migration is a very slow process because of the physical and chemical interactions with the environment and the low rate of water flow through the rock system. An acceptable value for the hydraulic conductivity in the rock at the repository level should be less than 1×10^{-3} m/yr. For this low magnitude, an effective delay of one hundred thousand to one million years to reach the biosphere is possible.

Assuming the geologic barrier would produce a delay time of 10^5 years, the collective dose to the world population will be exceedingly small. A repository containing the cumulative wastes resulting from the operation of six power plants of 600 MWe each over a 30 year period will generate a dose of 4×10^3 man Sv. This cumulative dose is similar to that received by the world population exposed to natural radiation for a period of 30 minutes.

For the hypothetical person in the future who drinks water that has been in contact with the radioactive waste, the resulting dose would be a few hundreths of an Sv. This is equivalent to a person being exposed to natural radiation for one half day. Finally, it is remarkable that such a low dose would actually occur after a hundred thousand years.

2.9. Project Schedule

The following gives the total list of events that will make up the Argentine project:

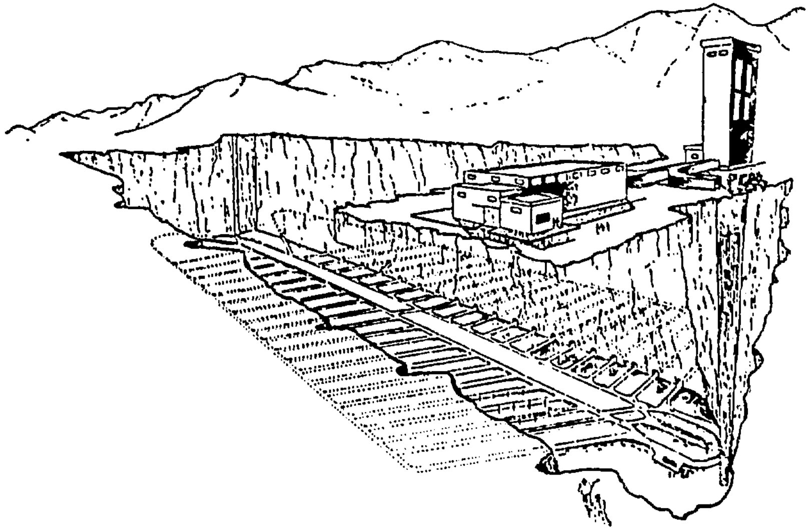

Figure 2.4. Schematic layout of repository.

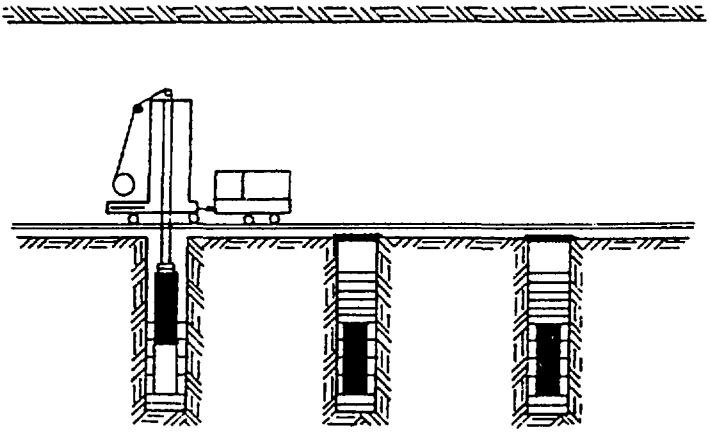

Figure 2.5. Placement of containers in repository with transport module.

1980 Begin survey of geological formations.

1982 Start feasibility study and basic engineering for repository construction.

1983 Begin corrosion study of container materials.

1986 Start geologic investigation of volcanic formations in Gastre area, 60 km area.

1987 Begin development of equipment for measuring hydraulic conductivity.

1990 Begin hydrogeologic study of the Sierra del Medio site: (a) Determine hydrogeologic features of area consisting of hydraulic conductivities of formations, chemical composition and age of groundwaters, temperature profiles, water pressures. Work will be carried out in wells drilled to 1000 m depth. (b) Model hydrogeological behavior of site.

1996 Start construction of exploratory vertical shaft.

1998 Construct rock mechanics laboratory at repository depth.

2002 Start engineering project.

2005/10 Begin repository construction.

2010/15 Start repository operation.

2070/75 Closure of repository.

2.10. References

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Chapter 3

Geoscientific Investigations in the Belgian R&D Programme Concerning the Disposal of Radioactive Waste in Clay

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3.1. Abstract

The prognosis about the wastes to be disposed of in a geological formation and arising from the Belgian nuclear activities up to the year 2050 points to amounts of 4,600 cu.meters of HLW (called type C), and of 20,000 to 25,000 cu.meters of alpha-waste (long-lived LLW and ILW, called type B). The policy of the National Radioactive Waste Management Board, NIRAS/ONDRAF/NERAS, aims at centralising all principal domestic waste management operations at one nuclear site in the northeastern part of the country, the Mol-Dessel site. Some treatment, conditioning and storage facilities are operational or planned at that site. A comprehensive, integral investigation project has been organised at this site focusing upon a particular clay formation, the so called Boom clay, as potential host rock. The first objectives of this project, the HADES project, are to demonstrate directly the technical feasibility and indirectly the long term safety of the disposal of conditioned HLW and ILW in an argillaceous hostrock. An underground research facility in the Boom clay is one of the major research tools.

3.2. Nuclear Waste Arising in Belgium

Several activities contribute to the present and near future waste arisings:

(1) The operation of the seven PWR-stations, reaching a total capacity of 5,540 MW(e), on two sites;
(2) Two nuclear fuel fabrication plants (an enriched uranium fuel fabrication plant and a MOX-fabrication plant);
(3) The reprocessing by COGEMA in France of the fuel burned in the Belgian power stations;
(4) The decommissioning and dismantling of waste treatment and conditioning facilities (e.g. the former Eurochemic reprocessing pilot plant);
(5) The production of radioisotopes and their use in industry, medicine and research.

In a more distant time frame an important volume of radioactive waste is expected to arise from the dismantling and decommissioning of the various existing nuclear facilities.

The detail of the waste volumes arising from the nuclear activities (launched in 1955) up to the year 2050 (end of the decommissioning phase of the installed facilities) is given in Table 3.1. The prognosis covers thus the waste production of about one century. The simpliest categorization of the waste types is adopted in this table. The following approximate waste amounts are expected to be generated up to the year 2050:

(1)	Type A :	120.000	cu.m
(2)	Type B :	20,000	cu.m
(3)	Type C :	3,900	cu.m

3.3. General Aspects of the Nuclear Waste Management Policy

The definition and implementation of nuclear waste management in Belgium has been entrusted to the National Radioactive Waste Management Board, named NIRAS/ONDRAF/NERAS (according to the national tongues). The policy of NIRAS/ONDRAF/NERAS aims at centralising at most all principle domestic waste

Table 3.1. Amounts of waste arising in Belgium up to 2050.

Origin	A	B (cubic metres)	C
Operation			
Power stations	21,950	80	-
Reprocessing	20,950	11,200	3,600
Fuel fabrication	800	1,100	-
Eurochemic	300	2,950	300
Research	2,850	-	-
Production and use of radioisotopes	4,500	100	-
Subtotal	51,350	15,430	3,900
Dismantling/Decommissioning			
Power stations	46,950	600	-
Fuel fabrication	2,000	100	-
Eurochemic	6,900	630	-
Research	10,500	3,000	-
Production and use of radioisotopes	2,000	-	-
Subtotal	68,350	4,330	-
TOTAL	119,700	19,760	3,900

management operations at the nuclear site of Mol-Dessel, in the northeastern part of the country. The site, which is easily accessible by conventional transportation routes, hosts treatment, conditioning and storage facilities, already operational. Furthermore, the fuel fabrication plants of Belgonucleaire and FBFC, the Eurochemic/Belgoprocess facility, the Nuclear Research Establishment SCK/CEN and the Central Bureau for Nuclear Measurement of Euratom are located at that site.

Several waste management and disposal scenarios are presently being evaluated. For the final disposal of type A waste, since dumping in the Atlantic Ocean sites is suspended, land based solutions are presently being investigated (shallow land burial, highly engineered structures at the surface and deep disposal). The important amount of category A wastes annually produced requires a final solution in the very near future. NIRAS/ONDRAF/NERAS has a procedure to submit a plan before 1992, for approval by the Belgian authorities, for the management and isolation of these wastes.

Most of the geoscientific research efforts over the last ten years have been devoted however to the isolation of wastes in categories B and C, for which the geological disposal option is now being evaluated. Up to now the focus was on the type C wastes, considered as being the most critical from the point of view of heat and radiation impacts on storage, handling, disposal and long term safety. The waste packages with the highest heat output within this category are the borosilicate glass wastes returning from the reprocessing facilities of COGEMA at La Hague in France. The thermal output of these waste packages at the time of their return to Belgium will be limited by specifications to 2,000 Watts per package and will be decayed to about 500 Watts per package after 50 years of intermediate surface storage. Taking into account the maximum permissible loading for the geological formation investigated (reckoned to be 2.5 Watt per sq. meter) an interim storage period of about 50 years has been adopted. A realistic disposal operation for this type of waste is thus seen to be in the year 2040 at the earliest. The thermal output of other heat generating wastes of type C is several times lower than that of type B and is thus negligible from that respect.

The reference scheme for the site investigation and demonstration programme will last until

2020. At that time, the construction of an underground disposal facility should be launched in the case of a positive appraisal by the authorities about the project.

3.4. Repository Programme for High Level Waste

On the basis of geological, geographical and other relevant scientific and technical information available in records, files and literature, a screening of potential geological host formations was made in the mid-70's. The screening factors adopted were:

(1) geological factors of the host rock itself, such as:
  - lithology (low permeability and/or porosity, homogeneity);
  - geometry (thickness, minimum 100 m for argillaceous, 200 m for evaporites and 500 m for hard rock, mineability, repository depth below 200 m, lateral extension minimum 50 sq. km, etc.);
  - specific characteristics: retention capability, plasticity or stiffness, insolubility in case of not very deep formations, insensitivity to waste impacts;

(2) site or areal factors, such as:
  - tectonic and seismic stability;
  - enveloping formations with low water transport rate.

In the screening procedure the geological factors resulted in a selection of potential formations (argillaceous rocks, hard rocks and evaporites), whereas the site and areal factors allowed one to identify areas with potential prospects for final disposal sites. The overall screening resulted in an identification of seven potential areas as indicated on Figure 3.1. All potential areas comprise potential host formations of the pelitia type: phyllites and shales of the Paleozoic and clays of the Cenozoic.

As can be seen on the map with of the potential areas (Figure 3.1) the nuclear site at Mol-Dessel is situated over two potential host formations: (1) the rupelian (Oligocene) "Boom clay" and (2) the westphalian formation called "Grande stampe stirile". The former, extending between about 180 and 300 meters below ground level at the site of the Nuclear Research Establishment SCK/CEN, has been taken as the case study for the Belgian programme and nearly all efforts were focused upon this particular clay formation under the SCK/CEN site. The Belgian programme is thus characterised by a formation and site specific approach.

3.5. The Concept of a Repository in a Subhorizontal Clay Formation

A mined repository concept with one disposal level has been developed taking into account a subhorizontal extension of the 100 m thick Boom clay formation (see Figure 3.2), its geotechnical characteristics, and the type C and B waste arisings and their characteristics.

A first concept was already developed in 1979 (Bonne and Heremans, 1985) taking into account the following hypotheses:

(1) Electronuclear power 10 GW(e), during 30 years, with reprocessing of all burned fuel, giving rise to 9,000 HLW canisters, 9,000 hulls canisters and 150,000 ILW drums;

(2) A maximum heat load of 1.5 Watt per sq. metre, corresponding to a cooling period of 50 to 70 years, 100°C increment in the host formation and a 5°C increment at the interface clay/overburden aquifers, and a thermal of 1 Watt/m. °C;

(3) Retrievability of the HLW and hulls-canisters during a longer time span after their emplacement.

On the basis of these hypotheses a concept was developed which contained the following subsurface features (see Figure 3.3):

(1) Two main access shafts with a useful diameter of 4.5 m;

(2) Ventilation shaft;

(3) Main adit or access gallery with a useful diameter of 3.5 m for disposing of:
  - HLW-canisters in vertical steel cased pits in the floor of three galleries (interdistance 250 metres and a total length of 7.5 km),
  - Hulls-canisters in vertical disposal pits in the floor of a 1,800 m long gallery,
  - ILW in the full section of three galleries (non-retrievable) with a total length of 7,500 metres.

All these structures were designed with conservative assumptions regarding the rheology of the Boom clay, which in the early phase of the programme was not well known.

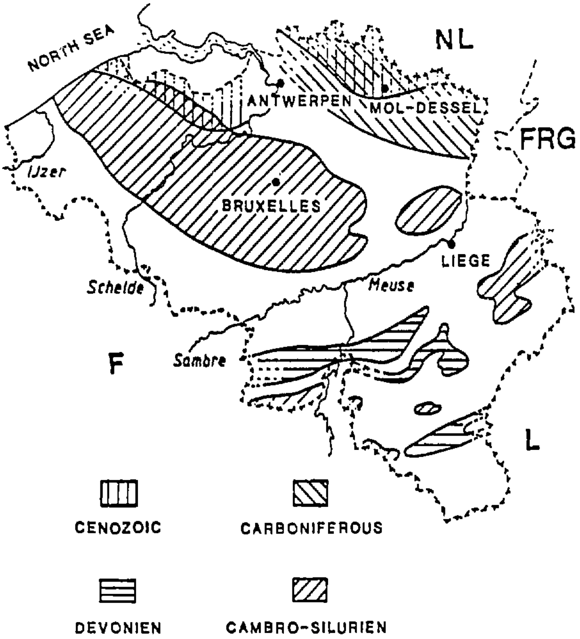


Figure 3.1. Map of potential geological formations for HLW and alpha-bearing waste disposal in Belgium.

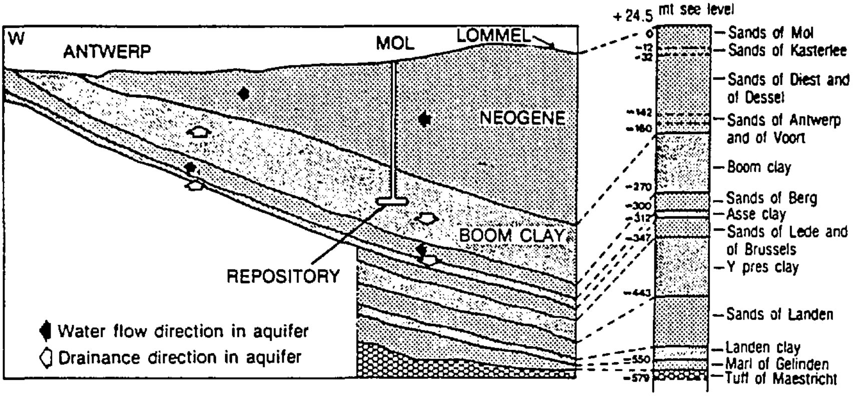


Figure 3.2. Schematized cross-section of the geological context at the Mol site and of the groundwater flow system.

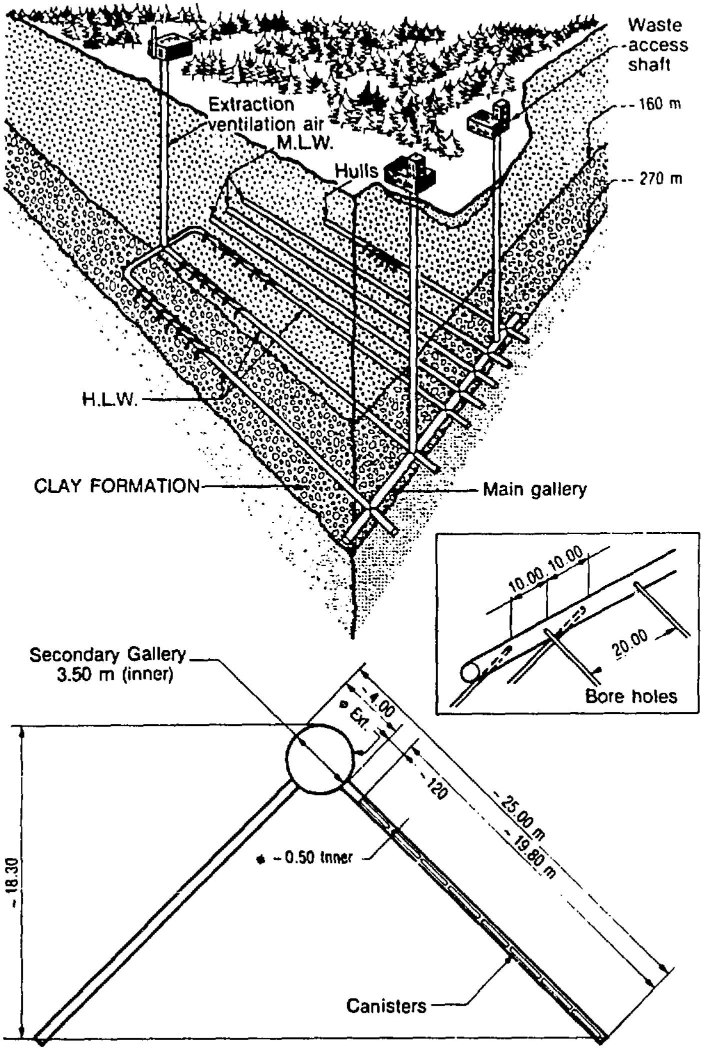


Figure 3.3. Concept of a HLW-repository in a stratiform clay formation. In-floor disposal principle (Mol Site, Belgium).

More recently, however, another concept has been developed that considers a new set of hypotheses:

(1) Present electronuclear programme, which is 5.6 MW(e), persisting for 30 years and other wastes arising from other nuclear plants (e.g. the waste produced by the pilot reprocessing plant of Eurochemic);

(2) Thermal loading of 2.5 Watt per sq.metre, with a corresponding cooling time of 50 years for the HLW-canisters; other assumptions related to the thermal aspects were identical with those of the earlier study.

This concept shows the following underground features (see Figure 3.4):

(1) Two access shafts of 6 m useful diameter;

(2) Two main galleries of 4 m useful diameter at 400 m distance from each other and of 1800-2000 m length;

(3) Seven transverse disposal galleries (emplacement in the full section) of 3.5 m useful diameter for HLW and concreted ILW, with an interdistance of 200 m;

(4) Seven transverse disposal galleries (emplacement in the full section) of 3.5 m useful diameter for bitumen ILW, with an interdistance of at least 20 m.

Of the two main concepts mentioned above several variants have been developed, each variant showing its own advantages and drawbacks. Other concepts could be considered in the next years.

3.6. Investigations at the Mol-Dessel Site

The main objectives of the present Belgian R&D programme on geological disposal of HLW are:

(1) to demonstrate the technical feasibility of geological disposal in a deep argillaceous formation; and

(2) to assess the safety of the concept.

These objectives are being pursued:

(1) through an extensive in-situ research and test programme in an underground facility (Figure 3.5) constructed in the Boom clay formation at the site of the Belgian Nuclear Research Establishment SCK/CEN at Mol (Bonne et al., 1985),

(2) through a regional hydrogeological investigation (see below), and

(3) through an appropriate performance assessment (see below). The emphasis on the in-situ testing in the site specific approach resulted in the acronym HADES (High Activity Disposal Experimental Site), to identify the project.

The present in-situ investigations and testing in the underground facility are organised according to the following structure:

(1) In-situ investigation aimed at improving technology related to in-situ measurements and observation, and at determining various in-situ characteristics related to:

   - corrosion of various waste package components (immobilisation matrices, container and canister materials) and structural components (concrete, cast iron, etc.) in an argillaceous environment;
   - geochemistry and migration of radionuclides, of corrosion products, of radiolysis products and of alteration products in clay;
   - geomechanics in relation to underground structures, and
   - backfilling and sealing of open spaces and voids.

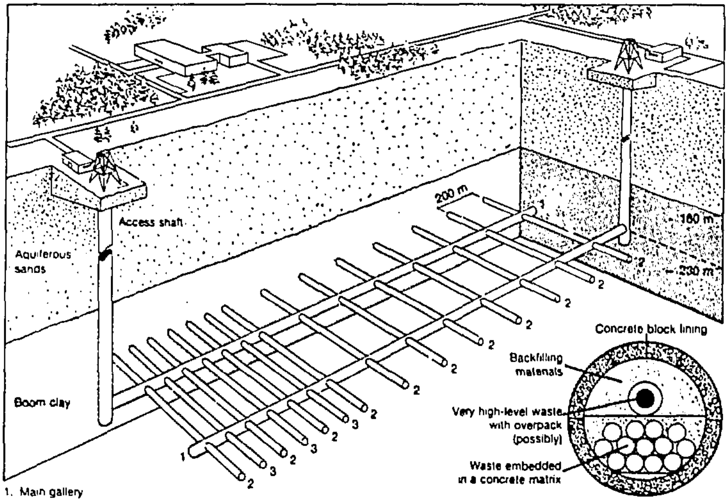
(2) In-situ tests aimed at the direct demonstration of:

   - mining capabilities and behaviour of mined structures;
   - near-field effects of combined heating and radiation;
   - interactions between the different waste package components; and
   - backfilling and emplacement capabilities, and backfill behaviour.

All the in-situ experiments mentioned above and discussed below are backed with "classical" laboratory investigations. One of our targets is to reach concordance between in-situ and laboratory approaches.

3.6.1. In-Situ Corrosion Experiments

An important series of in-situ corrosion experiments are currently underway (Debruyn et al., 1988; Van Iseghem et al., 1988). Nine experimental loops for studying the in-situ corrosion of various candidate immobilisation matrices, container and canister materials and structural components were installed in the clay immediately surrounding the underground laboratory. Some of these experiments are planned to last for five



1. Main gallery
2. Secondary gallery for burial of heat emitting waste combined with concreted waste (cf. section).
3. Secondary gallery for burial of bituminized waste and remaining concreted waste.

Figure 3.4. Concept of a HLW-repository in a stratiform clay formation. In-gallery disposal principle (Mol Site, Belgium) (Source: Niras/Ondraf/Neras, Brussels, Belgium).

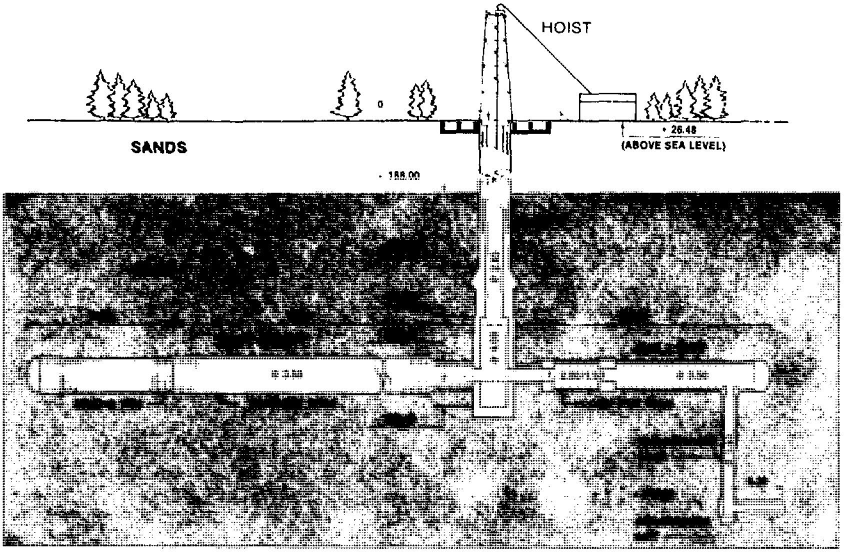


Figure 3.5. Scheme of the underground research facility HADES at the Mol Site.

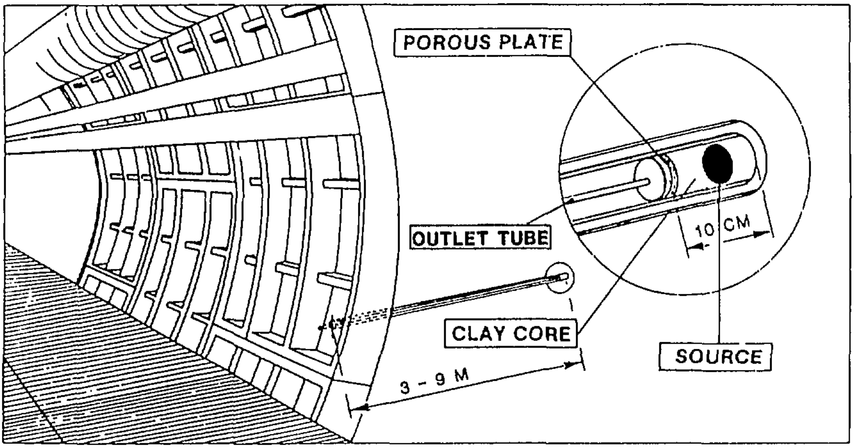


Figure 3.6. *Principle of the in situ migration experiments with percolation principle.*

years and as a consequence the last loops will be retrieved in 1993. They are functioning at ambient in-situ temperature, at 90° and 170° C.

Four experimental loops are running with direct contact between specimens and the clay, four others are operated such that the specimens are corroded by air or by volatile components released from the clay (chlorine for instance). One corrosion loop is a combination of both types. One corrosion loop of the direct contact type (90° C) has been retrieved after 586 days. Preliminary examination of the specimens allows one to conclude that there is a very good correspondence between the corrosion simulation testing and the in-situ testing.

3.6.2. In-Situ Migration Experiments

Several types of underground migration experiments (Monsecour et al., 1988) are actually being performed or are in preparation:

(1) Monodimensional percolation experiments with labelled clay cores emplaced in holes within the clay surrounding the underground laboratory. The principle of the experimental set-up is given in Figure 3.6. From the retrieved and analysed experiments up to now, we can conclude that the apparent diffusion coefficient for Sr calculated from the in-situ percolation test (Da = 6.9×10^{-8} cm sq.s^{-1}) is in fair agreement with that obtained from laboratory migration experiments (6.3 to 3.8×10^{-8} cm sq.s^{-1}). From the two Eu-migration experiments, it has been learned that the bulk of the activity remained in the source, but that the small released fraction is trapped in a very non-homogeneous manner. The procedure for the deduction of an apparent diffusion coefficient for Eu from such an experiment is not yet evident. Sr and Am percolation experiments are ongoing.

(2) Direct injection of non- or weakly retarded tracers in the clay formation. The principle adopted here is that tracers are injected in small screens emplaced within a borehole and are collected in neighbouring screens at 1.0, 0.2 or 0.05 metres from the source screen. For the time being only one injection test has been performed with HTO in a screen array with 1 metre distance between the screens. No results are available yet.

(3) Six more experiments of in-situ injection type are planned with HTO, Tc, Cs, Np, U and Pu.

3.6.3. In-Situ Hydrological Research and Observations

The targets for the in-situ research in this field (Bonne et al., 1988) are to:

(1) Establish the in-situ hydrological conditions for other experiments (e.g. migration experiments, geomechanical research);

(2) Confirm on a local scale the hypothesis and parameters of interest for the regional groundwater modelling system (e.g. hydraulic conductivity of the Boom clay, transit times for interstitial pore water).

In this regard, it should be mentioned that on the basis of a piezometer screen array in the terminal front of the underground laboratory and the observed interstitial pressures, the local hydraulic conductivity of the Boom clay has been calculated to be 2 to 3×10^{-12} $m.s^{-1}$.

3.6.4. In-Situ Geomechanical Experiments

A series of small scale geotechnical experiments (Neerdael and De Bruyn, 1988) (e.g. hole convergence, stress field measurements, instrumented tubes, dilatometer tests) and a mine-by test around an experimental drift allow one to infer that:

(1) The total convergence for a gallery with stiff liners and compressible intercollars is of the order of 1% of the diameter and the total convergence of the excavated clay wall is about 6 to 8%;

(2) The time dependent effects are clearly demonstrated by an "instantaneous" response that yields 80% of the deformation of the clay mass;

(3) A relatively low pressure level (1.5 to 2.2 MPa) acts on the structures and the stress field appears to be near isotropic.

3.6.5. In-Situ Backfill/Heater Experiment

This experiment is known under the acronym BACCHUS, which stands for "Backfilling Control and Heater Experiment for Underground Storage", developed jointly by CEA/DRDD of France and SCK/CEN.

The lay-out of the test is shown in Figure 3.7. The experiment consists mainly of a heating element simulating a reduced scale HLW-canister. The heating element is surrounded by bentonite blocks consisting of a "mixture" of Ca-smectite (50%), quartz sand (45%) and graphite (5%) precompacted at 20 MPa. The quartz sand was added to limit the swelling pressure to a value of 5 MPa, in agreement with the experimental conditions of the clay in the URL. The graphite is added to reach for the nonhydrated material a thermal conductivity about equal to that of the wet Boom clay (1.7 W/m°C). The backfill blocks are instrumented with humidity and temperature probes and pressure cells are placed on top of these compacted cylinders. On top of it a stack of 1.5 m of precompacted Boom clay blocks has been emplaced (equipped with pressure cells) to plug off the borehole and to enable the restoration of the initial conditions.

The surrounding clay host rock is instrumented with pressure (lithostatic and hydrostatic), humidity and temperature probes. This experiment which has been fully operational since spring 1989 will last for at least one year. The information gathered will be used to validate and calibrate thermomechanical and heat transfer codes.

3.6.6. The In-Situ Demonstration Tests Programme

The in-situ demonstration programme is organised around a set of specific individual tests which cover the targets mentioned above. The individual tests are documented below.

3.6.7. Construction of Test Drift (TD)

The objective of this test is to demonstrate the constructability and feasibility of real-scale galleries in deeper clays, without conditioning of the grounds prior to the construction and with the application of present day industrial techniques. In the construction test, two tunnel wall support techniques were tried out: a test of the stiff lining principle performed by SCK/CEN (Neerdael and De Bruyn, 1988) and a test of the converging lining principle performed for ANDRA of France (Andre-Jehan et al., 1988). The construction was performed in 1987 and the as-built lay-out of the drift in connection with the overall underground facility is given in Figure 3.5.

The length of the TD is sufficient so as to be representative for continuous tunnelling conditions. In the stiff concrete lined portion of the TD, 93 openings or ports were emplaced: 3 openings of diameter 760 mm, 20 openings of diameter 400 mm and 70 openings of diameter 200 mm.

Additional openings of diameter 105 mm can be bored at the intersection of 4 liners, without threatening the strength of the drift lining. The ports will be used as access holes for the implantation of auscultation and test devices.

3.6.8. Mine-By Test

A comprehensive observation programme (Neerdael and De Bruyn, 1988) is intended to meet the following purposes:

(1) Confirm the validity of the tunnel design;

(2) Monitor the response of the clay to the excavation on a real scale; and

(3) Provide long-term assessments on tunnel behaviour.

The ultimate objective of this test is to validate the geotechnical modelling of the gallery construction and of its behaviour in a plastic clay formation.

The following observations are performed:

(1) *Deformations of the clay in the roof* of the test drift. Deflectometer and settling devices were already installed before the excavation and construction of it was started in order to establish the initial state of the clay mass prior to the excavation of the TD as well as to monitor the excavation response. Deformations in the floor of the test drift were recorded by an extensometer emplaced in the course of the drift construction.

(2) *Pore water pressure measurements* are made by piezometers and hydraulic pressure sensors positioned in the floor of the TD and are intended to quantify the pore water dissipation and pressure history during the construction and thereafter. An extensive programme of measurements on the drift wall lining has been undertaken on the basis of instrumentation placed in several sections of the TD. Examples of such measurements concern the pressure on the lining, loading between the liners, deformation, convergence and displacements, strain and sliding of the steel ribs.

The terminal front also represents an important item of geotechnical observation. The displacements of the shotcreted shell covering the terminal front are monitored by 15 optical reflectors and the displacements within the front clay mass are measured with regard to an anchor emplaced at 10 metres in the mass, which is considered as fixed reference point.

A systematic topographic survey of the TD is undertaken periodically in order to follow as a function of time the displacements of the test drift and the reference points in it, with regard to a reference base line at the surface.

3.6.9. The CERBERUS Test

CERBERUS is a technological test aimed at evaluating by simulation the impact of a HLW-canister (50 years cooling time) on its immediate near-field. This test is conceived to be representative for some aspects of the in-gallery emplacement concept as well as for the in-hole emplacement concept. The simulating source for this experiment is a 0.45 × 10^6 GBq Co60-source combined with an electrical heating system (two heaters with a working power of 362 W each), all to be emplaced in a cased hole in the clay in the floor of TD and remaining in-situ during 5 years.

Auscultation in the clay includes monitoring of temperature, interstitial and total pressure, pH/Eh, doses. Auscultation in the gallery structure and the experimental set-up itself will include (when relevant): measurements on pressure, temperature, doses and deformation and trapping of volatiles. The concept of the CERBERUS test allows a limited number of additional studies on backfill and structural materials (dry and wet). A sampling and analysis of the clay and components of the experimental set-up are planned at the end of the test.

The concept of the test (shown in Figure 3.8) is designed in such a way that the radiation field as well as the temperature field of a 50-year old HLW-canister will be realistically simulated during a five-years period.

In this experiment Boom clay poured inside the test canister will be tested as backfill material. For the requirements of the experiment the material needs to be as dry as possible to avoid radiolysis and vapour production. It should have a density of 1.6 t/m^3 in order to simulate correctly the HLW radiation field in the host rock. Due to the complex shape of the test canister, it is not possible to use precompacted clay blocks. Therefore a 50-50 mixture of crushed highly compacted Boom clay ($\rho = 2$ t/m^3) and dry Boom clay powder will be used. After about five years these materials will be hydrated by interstitial clay water collected by a filter placed under the test canister. Its plugging properties in-situ will be evaluated by pressure probes. Sampling before and after hydration is intended.

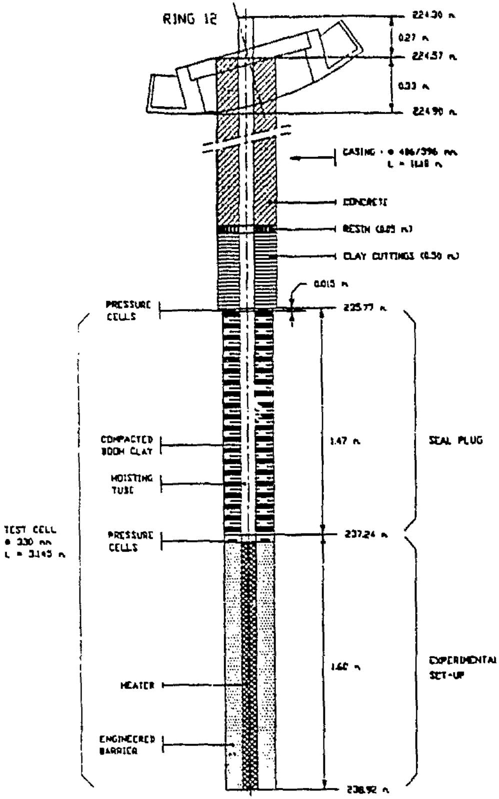


Figure 3.7. Scheme of the BACCHUS-experiment.

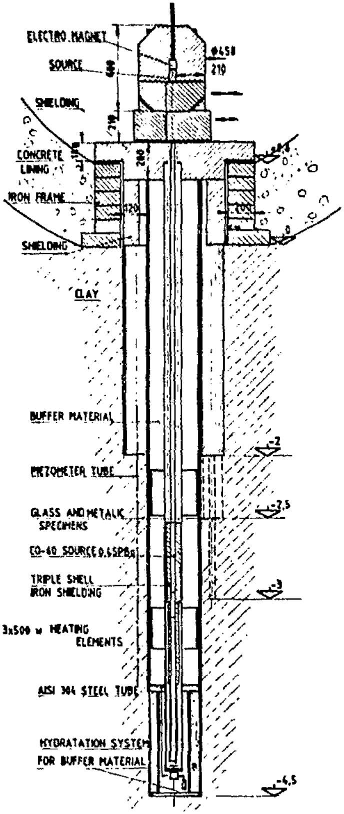


Figure 3.8. Scheme of the CERBERUS-test.

3.7. Regional Hydrogeological Study

3.7.1. *Geology of the System*

The regional geological structure (Patyn, 1987) is rather simple, as is shown on the cross-section in Figure 3.2. Tertiary deposits consist of a regularly layered sequence of alternating impermeable formations and sandy aquifers, which gently dip to the northeast. The sandy layers, dominating the regional groundwater system, are the Neogene sands above the Boom clay formation, the very-fine Rupelian sands underlying the Boom clay, and the calcareous Bruxellian sands, whereas the confining layers are the Boom clay, which is about one hundred meters thick in the Mol region, and the Bartonian Asse clay, some 25 m thick, separating the Rupelian from the Bruxellian sands. East of the studied region, this geological continuity is disturbed by faults that are related to the Rhine-Graben tectonics.

3.7.2. Regional Observation Network

The area considered in this regional study covers almost the whole of northeast Belgium. The network consists of 132 observation wells serving several purposes:

(1) Measurement of the waterlevel fluctuations in the aquifers to identify the flow system and to support the hydrodynamic modelling.

(2) Quantification of the hydrodynamic properties of the aquifers. Techniques that provide information about the spatial variability of the parameters, were preferred to a single accurate aquifer test, which yields only punctual information. For the confined aquifers of the Rupelian and the Bruxellian sands, the following techniques were selected:

- single-well pumping tests,
- classical slug tests,
- falling-head tests.

The transmissivity values (T) for the Rupelian aquifer calculated from the test, are in good agreement with a large-scale aquifer test that was carried out at the SCK/CEN site ($T = 10^{-5}$ m^2/s).

These techniques are not well suited for the highly-permeable Neogene-sand aquifer. Therefore, the global transmissivity of the aquifer was inferred by analysing the natural potentiometric fluctuations in the wells by a simple inverse model. A transmissivity of 3.8×10^{-3} m^2/s was derived on the basis of potentiometric and rainfall data observed during one year.

(3) Finally, the wells are also used for systematic sampling of the aquifers, in order to characterize them from a geochemical point of view, but also to establish a relationship between the flow pattern and the geochemistry.

3.7.3. Hydrodynamic Modelling of the System

On the basis of field data, the regional aquifer system was conceived as a multilayered system, consisting of three main aquifers: the Neogene sands that, notwithstanding their lithological variability, can be considered to behave as one aquifer; the confined Rupelian aquifer underlying the Boom clay; and the lowermost Bruxellian sands, separated from the Rupelian aquifer by the Bartonian Asse clay (Patyn, 1987).

The flow system was simulated by the French NEWSAM model, adapted to simulate the behaviour of large multilayered systems. In this case, the model was particularly interesting because of its flexible boundary conditions, especially in representing river systems, and the variable grid size that can be selected as a function of the density of the available data or the accuracy of the intended results.

As many uncertainties remain about the real boundaries of the system, the model boundaries were chosen far enough away from the Mol site to minimize their effect on the area of interest. As a consequence, the following hypotheses govern the model:

(1) In the outcrop areas, i.e. the Neogene sands and the southern limits of the confined aquifers, drain potentials are assumed, to translate the interaction between the surficial drainage network and the aquifers.

(2) To the east and north, no-flow boundaries were imposed. To the east, the system is assumed to be closed by the multiple faults belonging to the Rhine tectonics, or by the Meuse-Scheldt water divide for the Neogene aquifer. To the north, no evident features are present to fix a natural limit, and in this case a no-flow boundary parallel to the general E-W flow direction was imposed.

(3) An important assumption concerns the role of the confining layers: they act as one-dimensional joints that permit a hydraulic transfer between adjacent aquifers. It is believed that this leakage flow is fully Darcyan, and no threshold gradient is assumed to occur for the leakage flow.

The calculated potentiometric map for the Rupelian aquifer is represented in Figure 3.9. One observes a westward flow, essentially due to the distribution of the drainage potentials in the outcrop area. Nevertheless, the potentiometric pattern is also influenced by the leakage phenomenon, as the central potentiometric dome is obviously caused by leakage fluxes. Leakage discharges are revealed to be a major constituent in the hydrogeological balance of the Rupelian aquifer. It is noteworthy too that the model is very sensitive to the leakage coefficient, but nearly insensitive to changes in aquifer transmissivity. In the calibrated model, the hydraulic resistance of the Boom clay varies between 105 day/m and 5.14 day/m. Leakage flux entering or leaving the aquifer concerns very small quantities, but taking into account the large extent of the aquifer (several hundreds of km^2), it is obvious that this leakage phenomenon cannot be neglected when calculating the hydrogeological balance.

The general flow scheme for the whole system is represented in Figure 3.2; the natural flow in the aquifers is determined by the drain potentials in the outcrop areas and is east-west directed. In the eastern part of the considered region, where a disposal site is planned, regional analysis of groundwater flow indicates a downward movement in the Boom clay, while in the western half, calculations point out that leakage flow is directed upward. As far as the Bartonian clay is concerned, leakage is nearly everywhere directed downwards.

To validate this model and especially to check whether the leakage is a real phenomenon, several methods have been applied:

(1) Potentiometric observations;

(2) Application of environmental isotopes;

(3) Application of geochemical methods.

Additional wells were drilled to verify if the potentiometric dome predicted by the model actually exists in nature. As this dome can only be explained by leakage *through* the Boom clay, the potentiometric heads provide a good indication that leakage fluxes are probably correct.

As far as concerns the geochemical methods, the information collected is very limited because of the low density of the sampling points. The waterbearing formations can easily be discriminated from a geochemical point of view, but no firm conclusions can be drawn yet about the relationship between geochemistry and flowpattern. Also it was decided to check if a correlation between the groundwater age at various sampling points could be correlated with the hydrodynamic model.

3.8. Long Term Performance Studies

Within the framework of a concerted performance assessment on the European level, called PAGIS, the long term consequences have been evaluated for the disposal of conditioned HLW at the Mol site (in clay) among others. Detailed background information on this study is in the literature (Marivoet and Bonne, 1988), but it is worthwhile to recall here the main conclusions because they set the scene for identifying future investigation priorities on the basis of scenarios with highest probability of occurrence (natural degradation and faulting).

The most striking conclusion that we can draw from all the cases studied is that all calculations show that, for the case of the Boom clay at Mol, there will be no radiation exposure in the biosphere within a time span of ten to one hundred thousand years (see Figure 3.10).

If we really want to explore the very long time spans, the only numerically meaningful levels of radiation are calculated to occur around one million years (due to Technicium) and around ten million years (due to Neptunium and its daughter products). However, the calculated dose levels for the scenarios considered are orders of magnitude below natural background which, on the basis of common sense, would be considered as an acceptable reference. Although numerically meaningful figures are obtained, the intrinsic value of the doses calculated may be regarded as totally insignificant from the point of view of radiological impact.

The sensitivity studies have shown for the clay option that:

(1) The retention capability of the clay host formation dominates the overall system;

(2) The thickness of the clay barrier is a second important factor which determines the time of occurrence and level of radionuclide flux released by the host rock;

(3) The aquifer characteristics are of importance in defining the trajectories and the dilution rates;

(4) release rate from the near-field;

(5) the time of occurrence of the fault and the fault characteristics are of prime importance.

Taking into account that, for several parameters, the variability of their value has to be con-

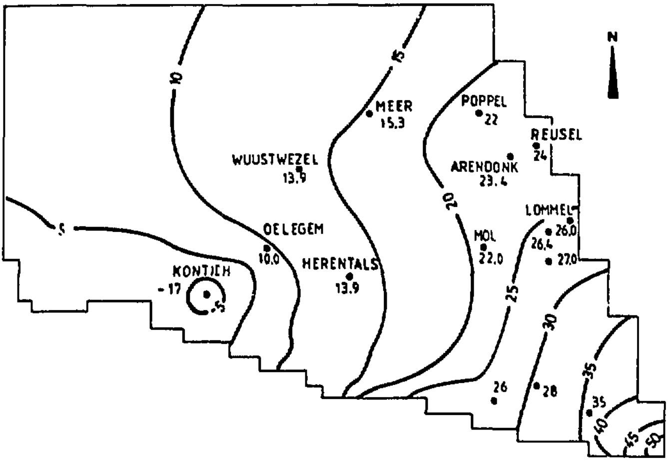


Figure 3.9. Calculated potentiometric map for the rupelian aquifer with comparison to observations in wells.

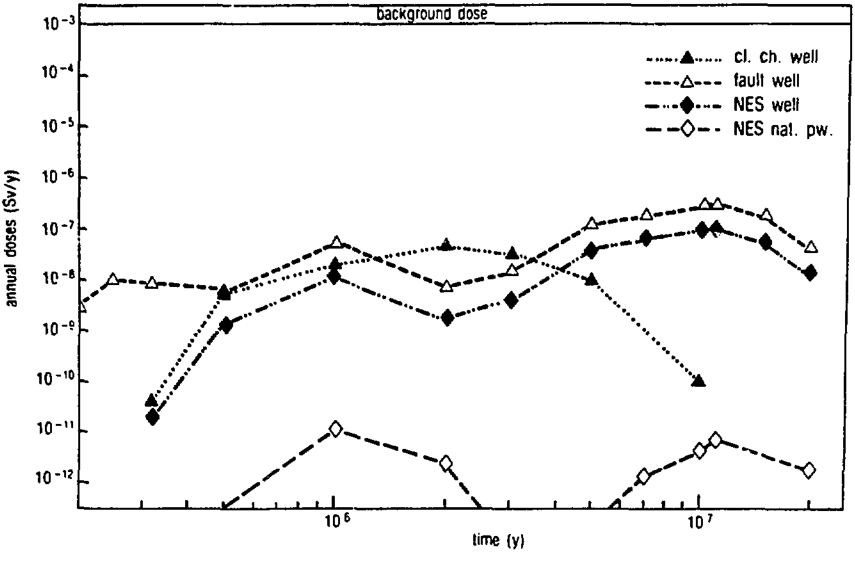


Figure 3.10. Comparison of total individual dose rates for the normal evolution scenarios (NES), climatic change and fault scenario at the Mol site resulting from the HLW-repository in the Boom clay.

sidered and that, for some parameters, their exact value is uncertain, appropriate assessments have been applied in coping with this particular part of the problem using uncertainty analysis. Not less than 12 cases have been analysed and 4,500 calculation runs were made. The main conclusion to be drawn from the uncertainty analysis in the clay option studies is that, taking the uncertainties in the model parameters into account, 95% of all the calculated doses do not exceed more than 100 times the best estimate doses and as a consequence, they all still fall fully within an acceptable area.

Still other conclusions may be drawn, for instance in the area of R&D needs:

(1) The conclusions about the limited importance of the near-field effects are only valid in case it can be demonstrated that these effects do not alter the large extent of the clay barrier thickness. Indeed the thickness of the clay barrier has proven to be a sensitive parameter. Intensive investigations are thus required to define and assess an acceptable near-field disturbance;

(2) The results are very sensitive to the retention capabilities of the clay barrier. It is thus evident that a thorough understanding of the migration and physico-chemistry of the radionuclides in the clay environment is needed;

(3) The results of the altered fault scenario indicate that this is the only relevant altered scenario which could be responsible for a noticeable deviation from the normal evolution scenario. Within this context the hydraulic disturbance in the faulted zone appeared to be the most sensitive altered parameter.

Some interesting conclusions can also be drawn with regard to site selection and characterisation:

(1) The very promising results obtained for the Mol site indicate that the site selection criteria set for the European Catalogue are realistic and appropriate;

(2) Performance assessments impose: (a) an emphasis on the characterisation of the clay layer, so that reliable predictions can be made about the retention capabilities of the clay barrier and (b) a careful examination of the hydrogeological system enveloping the clay barrier in order to define the real pathways toward the biosphere.

In relation to the development of concepts, it is to be concluded from PAGIS that the design has to be such that the near-field effects are kept within acceptable boundaries.

3.9. Acknowledgment

The author thanks Mr. P. Verougstraete, and Mr. P. Manfroy of NIRAS/ONDRAF/NERAS for their valuable comments and suggestions in the preparation of this paper.

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Chapter 4

Geological Considerations for Disposal of Nuclear Fuel Waste in Canada

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4.1. Introduction

Disposal deep in rock of a continental land mass is the most practical means to ensure permanent safety of nuclear fuel waste with today's technology. Continued storage of the waste would require that societal controls be kept in place far longer than could be relied on, even with the most optimistic view of the longevity of our society. Disposal under the seabed may be practical from a technical perspective, but would require international consensus on a scale that is likely not achievable. Other methods, such as transmutation of the radioactive species, are still the subject of research, but rely on advances in technology and very complicated processing, which may never be practical.

Consequently, geological considerations are extremely important to establishing the long-term safety of nuclear fuel waste. We will discuss how these geological considerations are being addressed by Atomic Energy of Canada Limited (AECL) in its assessment of the concept of disposal in plutonic rock of the Canadian Precambrian Shield. Our discussion will deal with three important aspects:

(1) Selection of a disposal medium for Canada,
(2) Characterization of potential disposal sites, and
(3) Prediction of long-term performance of a disposal system.

4.2. Background

Canada generates about 15% of its electricity from nuclear power, using CANDU heavy-water moderated reactors. There are 13 GWe installed and 3 GWe under construction. Eighty-seven percent of this nuclear electricity is produced in the province of Ontario, which derives 48% of its electrical power from nuclear generation. The remainder is generated by single reactors in the provinces of Quebec and New Brunswick.

There is about 13,000 Mg(U) of nuclear fuel waste in storage at reactor sites, all in the form of intact used natural uranium fuel assemblies. Additional used fuel is produced at a rate of about 1,800 Mg(U) per year. Although it is well established that used fuel storage is safe and reliable, and can continue for many decades, it is recognized that storage is not a permanent solution. In the 1970's, it was decided that disposal should be the final step in the nuclear fuel cycle. The objective was to isolate the nuclear fuel waste from the biosphere in such a manner that no responsibility or burden would be passed on to future generations.

In 1978, the governments of Canada and the province of Ontario entered into an agreement to cooperate in the development of technologies for the safe permanent disposal of Canada's nuclear fuel waste (Joint Statement, 1978). Under this agreement, Ontario Hydro, the provincially owned utility, is responsible for research on interim storage and transportation, while AECL, a federal crown corporation, is responsible for research on immobilization and disposal. In 1981 April, the Canadian government approved a ten-year generic research and development program to assess the concept of nuclear fuel waste disposal deep in plutonic rock of the Canadian Shield (Joint Statement, 1981). The results of this generic research will be reviewed under the Federal Environmental Assessment and Review Process. The Environmental Impact Statement for this review will be submitted by AECL in 1991 for an in-depth scientific and technical review followed by public hearings. No screening or selection of potential disposal sites can be undertaken before a decision is made by the governments following the hearings.

The research and development program has had three primary goals:

(1) to develop and demonstrate technology to site, design, build and operate a disposal facility in plutonic rock that will satisfy Canadian regulatory safety criteria,

(2) to develop and demonstrate a methodology to evaluate the performance of a disposal system against the safety criteria, and

(3) to show that suitable sites in plutonic rock are likely to exist that, when combined with a suitably designed facility, would meet the safety criteria.

In Canada the nuclear regulatory agency is the Atomic Energy Control Board (AECB). In addition to the regulatory requirements that apply to existing nuclear facilities, the AECB requires that following closure of the disposal facility no individual should receive an annual radiation dose greater than 0.05 mSv (compared to the 1 mSv received annually from natural sources). It must be shown quantitatively that the safety criteria would be satisfied for a period of 10,000 years (AECB, 1987).

We have adopted a passive multi-barrier concept for disposal that combines the containment provided by the structural, hydraulic and geochemical characteristics of the rock mass with a series of engineered barriers. The conceptual disposal vault consists of an array of disposal rooms excavated in plutonic rock at a depth between 500 m and 1,000 m over an area of about 4 km^2. Cylindrical containers of waste would be placed in boreholes in the floor of the rooms surrounded by a compacted mixture of bentonite and sand. The rooms would be backfilled by compacting a mixture of clay and crushed granite in the lower portion of the room and pneumatically filling the top portion with bentonite and sand. Concrete bulkheads would seal the room entrances. Closure would be achieved by backfilling the access tunnels in the same manner as the rooms and then backfilling the shafts with compacted clay and crushed granite separated by a series of supporting concrete bulkheads.

4.3. Selection of a Disposal Medium for Canada

When AECL began the research and development program on nuclear fuel waste disposal it was clear that available resources would not permit intensive research on a number of media. Therefore, we adopted the approach of identifying the most attractive geological medium for Canada and concentrating available resources on assessing the suitability of that medium. The Geological Survey of Canada (GSC) was requested by AECL to evaluate the suitability of geological formations in Canada for disposal (Dyne, 1975). A primary consideration in this evaluation was the fact that, because the province of Ontario was, and would continue to be, the principal region in Canada for the development of nuclear power, the first disposal vault would most likely be located there. Therefore, the research program would have to be relevant to disposal in Ontario. As a result of the evaluation by the GSC, AECL made the decision to focus research on the concept of disposal in the plutonic rock of the Canadian Precambrian Shield, which is predominant over a large portion of Ontario, and has features that appear to make it an excellent medium for the disposal of nuclear fuel waste.

4.3.1. Disposal Medium Selection Philosophy

The design of a disposal facility, and any assessment of its performance and long-term safety, will depend not only on the geological medium in which the waste is emplaced, but also on many other medium-independent features specific to the site, such as the regional geological setting and features of the surface environment. Therefore, it is not possible to determine in a generic sense that any one of the various major geological media that have been proposed for nuclear fuel waste disposal is "best" technically. However, it is possible to determine in a national context which of the potential disposal media offers the greatest flexibility and potential for success in site selection, while having characteristics that make it a technically suitable medium for safe disposal. Hence, in Canada, plutonic rock is favoured, because it allows the greatest scope for the application of social, political and economic factors to selection of the eventual disposal site.

4.3.2. Candidate Geological Disposal Media for Canada

Most of the potential media for geological disposal that have been proposed internationally occur in Canada. However, only three can be supported as serious candidates in the Canadian context: plutonic rock of the Precambrian Shield, bedded salt deposits of the interior sedimentary basins, and shales of the interior sedimentary basins. Other rock types such as unmetamorphosed tuff and basalt and diapiric salt deposits (salt domes) occur, but selection of any of them would severely limit flexibility in siting and would virtually prohibit disposal in the Province of Ontario. These media also occur in regions of relatively high seismic risk (Zone 2 or above) in comparison to the bulk of the Precambrian Shield and the interior sedimentary basins (Zones 0 and 1). Metamorphosed tuff and basalt do occur on the Precambrian Shield, however they commonly occur in areas of significant mineralization and are often associated with ore bodies. Consequently, on the Shield deposits of tuff and basalt would usually be avoided rather than sought as potential disposal media.

4.3.3. Plutonic Rock As A Disposal Medium for Canada

Within the broad classification of plutonic rock are included all rocks crystallized from a molten state deep within the earth's crust. Large individual intrusives (plutons) have been the main focus of the research effort because these bodies tend to be of relatively high compositional uniformity and structural integrity. By far the greatest number of plutons in the province of Ontario are granitic (75%) or gabbroic (15%) (McCrank et al., 1981). Therefore, we decided that both granitic and gabbroic plutons would be investigated. Our field research has also included investigations on the metamorphic rocks surrounding the plutons.

The following considerations justify the continuing focus of the program on the plutonic rock option:

(1) Plutonic rock of the Canadian Shield is exposed over large portions of five of the ten Canadian provinces and of the Northwest Territories. Some plutonic rock is exposed in all the provinces except Prince Edward Island. In Ontario, the Canadian Shield extends over more than 600,000 km^2, and more than 1,300 individual plutons have been identified. Thus there are a large number of potential sites in plutonic rock, which occur over a wide range of geographical conditions, so the siting process will not be unduly constrained by technical considerations.

(2) The Canadian Shield has been relatively stable for at least the past 600 million years. The Superior Structural Province, which constitutes the largest area of the Shield in Ontario, has not had major orogenic activity for 2,500 million years. It is not a large extrapolation, therefore, to infer that the region will remain relatively stable for the next million years.

(3) Field and laboratory investigations, together with theoretical analyses of rock creep indicate that underground excavations in good quality plutonic rock are stable and should experience very low time-dependent deformations during the minimum design life of the containers (500 years). Thus it may be inferred that lithostatic stresses will not be transmitted to waste containers in the early years of the vault. This facilitates the development of safe, long-lasting containers, and enables the use of existing excavation technology in vault engineering and construction.

(4) Regional topographic gradients in the shield are low, in the order of 10^{-3} (1 m/km). This is an indication that natural driving forces for groundwater flow deep in the rock may be low, as substantiated by hydrogeological testing at our field research areas. Since transport in groundwater is the only significant potential mechanism by which radionuclides could be brought to the surface from a deep vault, the presence of a generally low driving force suggests that regions can be found where transport of any radionuclides leaking from the vault would be inhibited by very slow groundwater flow.

(5) There are large volumes of plutonic rock with extremely low porosity and permeability. This would serve to limit access of groundwater to the waste, thereby slowing deterioration of the engineered containment, and of the waste form itself, and inhibiting transport of radionuclides through the rock.

(6) Minerals in plutonic rock are found to react with many of the radionuclides in nuclear fuel waste in such a way as to prevent or greatly retard their movement through the rock. Since the radionuclides decay with time, retention and retardation serve to decrease the potential impact on the biosphere.

(7) Many of the plutons in the shield are not associated with economic mineral deposits. Because of this, mineral exploration in these areas is expected to be low in the future. Therefore, the possibility of accidental intrusion into the vault by man is remote.

4.4. Characterization of Potential Disposal Sites

The rock mass surrounding the disposal vault is expected to provide the principal barrier to the migration of radionuclides, if they are released from the waste container. Transport in groundwater is the only significant potential mechanism by which radionuclides could be brought to the surface from a deep disposal vault.

Consequently, a knowledge and understanding are required of the potential groundwater flow paths through the rock; the chemistry of the groundwater and the rock; the mechanisms of thermal, mechanical and hydrological response of the rock mass that might alter the potential flow paths and chemistry; and the mechanisms of radionuclide transport and retention along the potential flow paths.

By site characterization we mean the process of field and laboratory investigation by which this knowledge and understanding are obtained.

4.4.1. Important Geotechnical Factors

We consider the following factors to be important in characterizing sites:

- tectonic and structural setting,
- nature of major lithologies and contacts,
- properties and history of sealed fractures,
- properties and history of fluid-filled fractures,
- properties and history of rock alteration, chemistry and mobility of fluids,
- fluid pressure field,
- rock stress and thermal fields,
- nature of local topography,
- nature and distribution of soils,
- local meteorology,
- surface water hydrology, and terrestrial and aquatic biology.

The first two factors largely determine both the long-term stability of a site and the nature of the responses of the rock to excavation and to the thermal and hydrological perturbation caused by a disposal vault. They also affect the nature and extent of anisotropy and heterogeneity in physical properties of the rocks at the site. The physical and hydrological properties of different lithologies may be significantly different and the contact between lithologies may represent a significant physical or hydrological discontinuity.

Fractures in the rock provide the potential pathways for groundwater flow and radionuclide migration. Both sealed and open fluid-filled fractures must be investigated. An understanding of the origin of the fractures and the processes responsible for sealing and rejuvenating them is needed to evaluate the potential for changes in the existing open fracture network due to the perturbations caused by the excavation of the vault, the thermal transient of the disposed waste and any likely future disruptive events.

Alteration caused by changes in the physical, hydrological and geochemical characteristics of the rock and the existing chemistry of the fluids in the rock is the observable end result of the natural processes of fluid-rock interaction that have taken place within the context of the hydrogeology of the site over time periods equivalent to those of concern for long-term safety assessment. An understanding of these processes is needed so that the waste form and engineered barriers can be optimized for stability and longevity in the hydrochemical environment that will be present following disposal.

Fluid pressure, in-situ stress and temperature are the primary dynamic parameters in the rock mass. The distribution of these parameters must be known before appropriate boundary conditions can be specified for mathematical models to simulate the thermal, mechanical and hydrological responses of the rock mass to the disposal vault. Variations in these parameters must be measurable with time in order to obtain the observational data required for comparison with predictions from the model simulations.

The final five factors are critical to determining the environmental sensitivity of the disposal site, primarily the susceptibility of the area to environmental damage during construction and operation of a disposal facility. The topography also largely determines the distribution of areas of groundwater recharge and discharge. Taken together, these factors determine the nature of the biosphere and they must be understood to develop appropriate models of biosphere processes to be used in environmental and safety assessments.

4.4.2. Site Characterization Methodology

The initial reconnaissance investigations employ the traditional methods of field geology, mineral exploration and terrain analysis. This involves essentially a review of existing geotechnical information and an analysis of satellite and aerial photographic imagery and topographic maps. More detailed surface and subsurface investigations would then follow. The surface investigations would include detailed mapping of lithology and structural features in outcrop; gravity, magnetic, VLF-EM and shallow seismic refraction surveys; and establishment of a monitoring network for meteorological and surface hydrological data.

The initial surface investigations provide two types of information that are of particular importance to the development of subsurface investigations. First is the identification of features that may represent the surface expression of major discontinuities in the rock. Generally, these would be major linear features observable on satellite images and aerial photographs or significant anomalies identified from the geophysical surveys. Second is the identification of structural features that provide information on the stress field and potential anisotropy in the bulk rock properties. Generally, these would be orientations of vertical joint sets or identification of different lithostructural domains within the rock mass in outcrop.

Guided by information obtained in the initial surface investigations, cored holes are diamond-drilled into the rock at strategic locations to depths exceeding 1,000 m. Detailed logging of the oriented core as it is recovered provides information on the location and character of fractures as well as a range of other structural and lithological parameters. Accurate borehole deviation surveys and a range of geophysical surveys are run in the completed boreholes to identify variations in rock properties and lithology with depth as well as to identify fracturing in the rock (Davison et al., 1984).

Figure 4.1 shows the conceptual model of rock structure indicating the scales of major fracturing in relation to the size of a disposal vault.

Usually the fracturing is concentrated in narrow zones (about 1 m thick that may be hydraulically active. Steel casings fitted with valves and sealing systems are inserted in the holes to isolate the fracture zones and allow the hydraulic properties of the zones to be monitored (Davison, et al., 1984). The chemical composition of water samples taken from the zones is determined to provide further information on the character of the flow system and the rock mass.

The hydraulic monitoring system is used to determine the interconnection and hydraulic conductivity of the various structural zones in the rock. This is done by either injecting or withdrawing water from an isolated interval and measuring the response in the other intervals in the system. Also, the responses observed in all the intervals following periods of heavy rainfall and snow melt provide vital information on the character of the flow system.

Selected cores from the boreholes are used to determine a range of rock properties in the laboratory. Measurements are made for porosity, permeability, uniaxial compressive strength, elastic modulus, Poisson's ratio, compressive wave velocity, tensile strength, thermal conductivity, thermal diffusivity and magnetic susceptibility. Additional geomechanical information is obtained by measuring in-situ stress in selected boreholes using the overcoring stress determination method.

4.5. Prediction of Disposal System Performance

The geological investigations provide information vital to all aspects of performance assessment. They determine the pre-construction groundwater regime in the area, and so are vital to predicting the post-closure flow system. They provide the baseline in-situ chemistry from which the chemical evolution of the disposal vault is determined. They provide the physical and structural rock properties, which allow prediction of long-term rock mass response to excavation and heat, and definition of transport pathways and properties. Finally, they provide a knowledge of the potential entry points for contaminants to the surface environment.

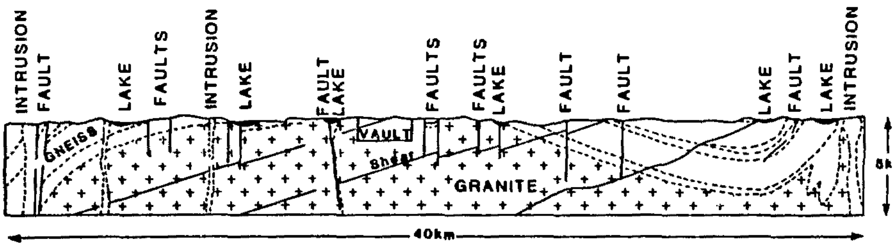

Figure 4.1. Schematic cross-section showing the general nature of structural and lithological features anticipated in association with granitic plutons in the Canadian Shield of Ontario.

The emphasis in the Canadian regulatory guidelines and requirements is on overall disposal system performance criteria rather than prescriptive criteria for individual components of the disposal system. Also, there is a recognition that the evaluation of long-term performance of a disposal system must be based on estimates provided by mathematical modelling because no long-term performance histories of comparable facilities exist. An important aspect of our geological research is the development of a methodology for modelling the site groundwater flow system.

Based on the surface and borehole information, a conceptual model of the groundwater flow system is developed that can be represented by a detailed three-dimensional mathematical model. The mathematical model of the flow system is calibrated against the field measurements of hydrogeological conditions and responses to field tests. Once the model is satisfactory, the conceptual design of the underground facility can be included in the model and the long-term behaviour on the flow regime analyzed. This analysis is used in the assessment of potential environmental impacts. Both the detailed flow and transport analyses and the environmental and safety assessment would provide feedback for engineering design constraints in the preliminary design for the repository.

An important requirement of the site characterization methodology is that it provide for an appropriate demonstration that the understanding of the site is valid. This demonstration is the last component in the pre-construction characterization program and entails predicting the response of the rock mass to excavation of an exploratory shaft and then excavating and characterizing the shaft. Construction characterization of the shaft will provide the rock mass response data and properties needed for the underground facility design and to develop the detailed requirements for characterization work during underground excavation and construction.

The lack of directly comparable past engineering history and the requirement for long-term predictions of system performance make it imperative that our understanding of the geological conditions at the site be tested sufficiently often and in enough depth to give confidence that it is adequate. To do this, we would establish an array of monitoring instrumentation throughout the volume of rock that would be affected by the disposal vault. This volume would include all the identified major potential pathways for migration of contaminants from the vault to the surface. The observations from this monitoring system are used for continual comparison of actual conditions as vault construction and operation proceed against expected conditions. Observations are used to improve the models and to enhance the monitoring system.

The continuous program of prediction of system behaviour and comparison of the predictions with observations is conducted throughout the construction, operation and eventual closure of the disposal vault. Whenever a decision is required, a history of previous predicted and actual performance will always be available to provide support for the validity of predictions. By the time a decision is made regarding closure of the vault, there will have been close to a century of observation and model development. A detailed well-documented observational engineering record of that length will provide an excellent basis for the final model predictions in support of closure.

Thus, thorough site characterization including hydrogeological, geomechanical and environmental monitoring before construction, during operation and after closure is critical to providing assurance to regulatory bodies and the public that the models used and the resultant estimates of future performance are reasonable.

Although the siting process would stop with licensing of a site, site characterization must continue throughout the operating lifetime of the disposal facility in order to obtain the information needed to support decommissioning and closure. Monitoring of hydrogeological, geomechanical and environmental conditions begun before site licensing should continue for several years after backfilling the repository and sealing the shafts in order to demonstrate the proper functioning of the engineered systems and to justify discontinuing institutional control of the site.

4.6. Case Study for a Plutonic Rock Disposal Vault

While it is clear what is meant by safety of a disposal facility, it is far less clear what is meant by safety of a concept. We would implement the concept at a particular site. The design of the facility will depend on the characteristics of the site to a greater extent than for most projects, because the rock is an integral part of the facility, not just a foundation. The characteristics of the specific disposal site are important to the potential impacts, and to the design of the engineered components. Although some of these important characteristics can be defined in generic terms as being common to plutonic rock of the Shield, most will vary from site to site.

Therefore, in assessing the suitability of the "concept" of disposal in plutonic rock, we do not consider it meaningful to do a quantitative analysis of a set of generic site and system characteristics. Instead, we have applied the methodology outlined above for assessing the safety of a disposal system to a case study that derives its site-specific information from an actual field research area. This achieves two purposes. First, it demonstrates that the capability exists to perform the environmental and safety assessment that will be required to implement the disposal concept. This includes acquisition of data, interpretation of information in analyzing the natural and engineered systems, and estimation of potential impact. Second, as we shall show, it demonstrates that the requirements of a safe disposal site are compatible with the characteristics found in the Shield. This makes it evident that a site can be found on which to develop a safe disposal facility.

To describe the characteristics of the rock and associated groundwater flow system in the case study, we have used information from the Whiteshell Research Area. The geological environment of the vault is thus consistent with information taken from an actual shield area. This makes the case realistic in the sense that site characteristics employed in the study are representative of an actual field situation. On the other hand, it is hypothetical in the sense that some of the areas at the Whiteshell Research Area have not been completely explored, so details in these areas are not necessarily accurate. Lack of accuracy in important areas would of course be addressed by further information gathering if the objective were to evaluate the site for possible implementation of an actual disposal facility. However, our purpose is only to conduct a suitable case study to provide information for our assessment of the disposal concept. Accuracy in detail is not important for this purpose, as long as any assumptions made regarding that detail are realistic or conservative.

The Whiteshell Research Area is located near the Whiteshell Nuclear Research Establishment in southeastern Manitoba. It includes a large portion of the Lac du Bonnet Batholith, a large granite pluton. The pluton was intruded over 2,500 million years ago into the rocks existing at the time. The pluton itself, the surrounding rocks and the interfaces between them have been the subject of extensive field investigation over 10 years.

Figure 4.2 is a map of the research area showing some of the major surface features of the Lac du Bonnet batholith. For our concept assessment, we assume that a vault is located at a depth of 500 m, centered about the Underground Research Laboratory (URL). Figure 4.3 shows a vertical cross-section (the line AA' in the map), which intersects the hypothetical vault. Most of the detailed information, such as orientation of fracture zones and the five rock layers, are based on detailed studies carried out at the URL (section BB', Figure 4.3). Geological structures outside the boundaries of the URL have been conjectured since no information from depth was available in those regions.

A three-dimensional groundwater flow model of the area has been constructed using the conceptual structure shown in Figure 4.3. The model has been calibrated with observations of groundwater response to pump tests and natural perturbations of the groundwater system, and validated using the response of the flow system to excavation of the URL (Davison and Guvanasen, 1985; Guvanasen et al. , 1985). It is being used to determine the flow paths from the hypothetical vault to surface. Other models are then used to simulate transport of material from the vault to surface along these paths (Reid et al., 1989). Information such as rock and groundwater chemistry is determined from field investigations and used in these transport models. This shows how the geological information from the site characterization feeds into the assessment of disposal vault performance.

4.7. Conclusion

Geoscience Research in the Canadian Nuclear Fuel Waste Management Program has established an effective technology for evaluating plutonic rock sites as disposal sites, and for designing and constructing a disposal vault in plutonic rock. Given the wide availability of potential sites in this rock and the characteristics that have been observed at research areas in the shield, plutonic rock is an excellent choice for development of a future disposal vault for Canada.

The geological field investigations required to establish a disposal facility can be carried out with present day technology, although accuracy and reliability of information will benefit from advances in instrumentation and procedures. These field investigative techniques have been demonstrated at field research areas on the Canadian Shield.

Mathematical models based on geological field information will play a vital role in establishing a disposal facility for nuclear fuel waste. It is important to recognize the strong relationship between site-specific geological information and the mathematical models used to predict

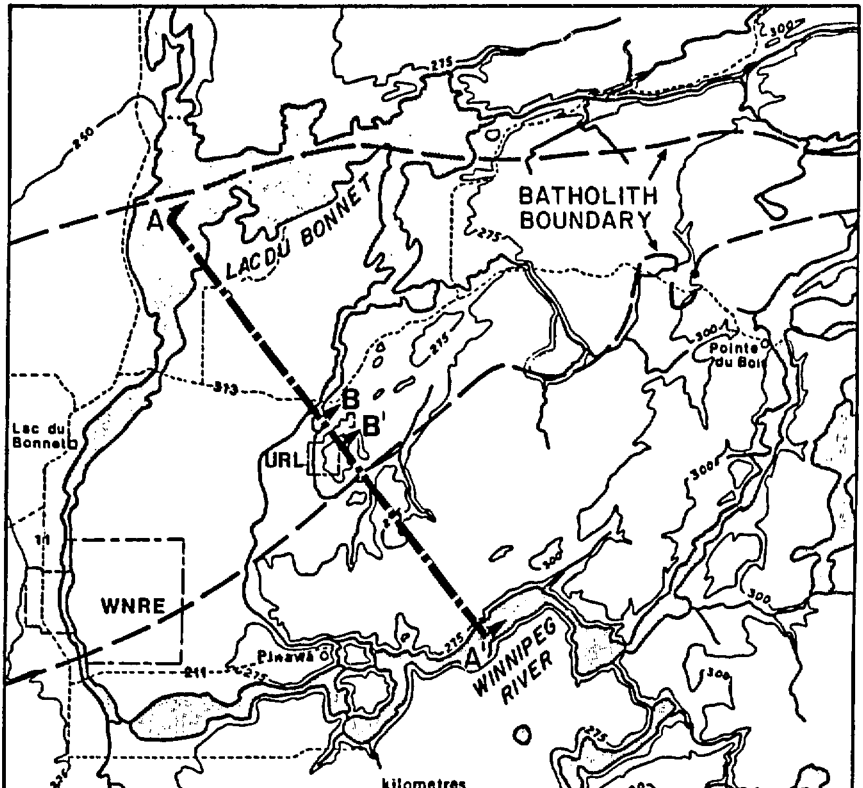

Figure 4.2. Location map of the Whiteshell Research Area showing the Lac du Bonnet granite batholith, surface topography (25 m contour interval), drainage and the location of the cross-sections in Figure 4.3.

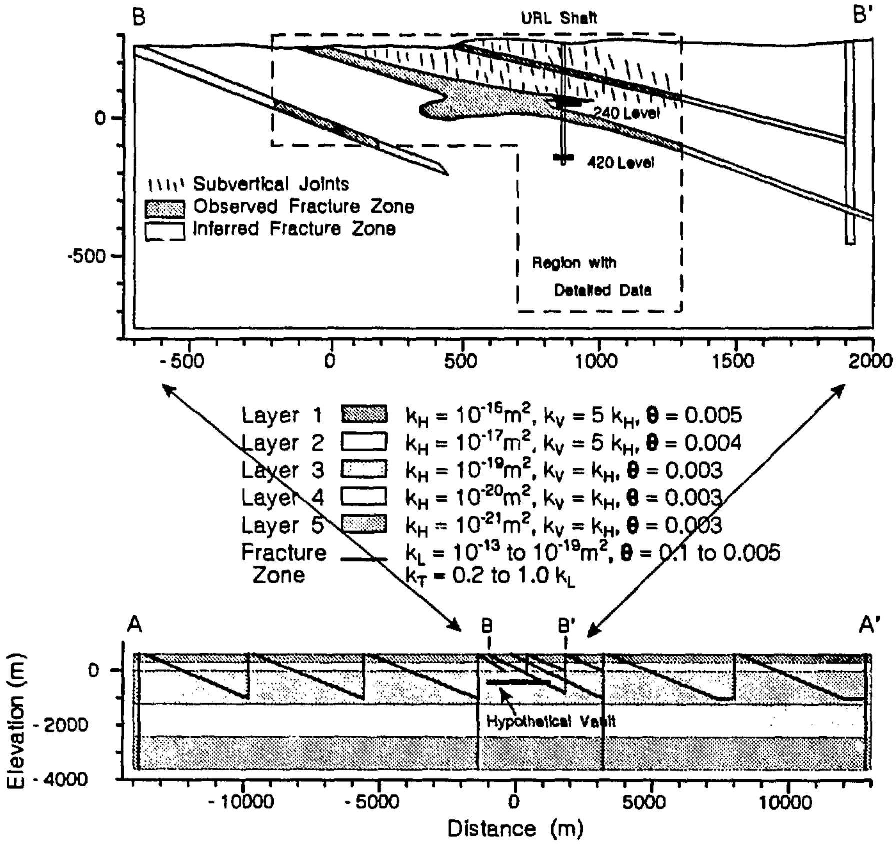

Figure 4.3. Conceptual cross-section (A-A') used for mathematical modelling of groundwater flow at the Whiteshell Research Area based on detailed investigations at the Underground Research Laboratory (B-B'). Patterns in section A-A' represent the distributions of horizontal and vertical permeability (K_H, k_v) and porosity (θ) employed. The ranges of lateral and transverse permeability (k_L, k_T) are also given for the fracture zone.

disposal system performance. We have developed a methodology that we believe will lead to successful development of predictive models. These models will be developed progressively over the sixty to seventy years required to site, construct, operate and close a disposal facility. They will be used to predict future system behaviour at each stage, and modified as necessary to represent all known historical information. There will thus be a very high level of confidence in the validity of the final predictions based on a long record of detailed observations of the actual disposal system.

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Chapter 5

Feasibility of Preselecting Sites for Disposal Repositories of Nuclear Wastes in China

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5.1. General Description

In the exploitation and utilization of nuclear energy, the government of China is greatly concerned with radioactive waste management. The various disposal techniques now being developed are very important at this stage of development. Radioactive waste management in China comprises waste handling and waste disposal. The former mainly includes waste incineration, volume reduction, solidification, packaging, container transportation, storage and so on. The latter focuses on the selection of sites, the study of shielding and backfilling materials, establishment of underground laboratories and experiments, nuclide migration, assessment of environmental safety, design and construction of disposal repositories, final disposal implementation and management, etc.

This report chiefly introduces the feasibility study since 1985 of preselected sites in China for disposal repositories for radioactive wastes. According to the requirements and conditions for site selection, and on the basis of a comprehensive analysis and comparison of regional geological data obtained from all over China, six areas have been selected as the first set of preselected sites. These are located in northwestern Gansu, western Zhejiang, northern Fujian, central Inner Mongolia, southwestern Shaanxi, and central Guangdong. These sites are being analyzed and compared in terms of lithologic type, geologic structure, seismic conditions, hydrogeology, and physical and economic geography, as well as strategic distribution of the nuclear industry. Feasibility studies and a reselection have been done in these areas.

China has a vast territory with various geological phenomena. In order to lay a sound foundation for site selection and evaluation of engineering geology, hydrogeology, radioactive nuclide migration and safety, we give first priority to areas of granitic rocks as sites for high-level waste repositories. We considered areas of tuffaceous rocks and clay formations as the disposal sites for low and intermediate-level radioactive wastes.

5.2. General Conditions for Site Selection

In general, the conditions for site selection may chiefly be of two aspects: social and natural. The social conditions mainly include six points as follows:

(1) Strategic distribution of nuclear industry. For example, the distribution of the sources of radioactive waste material, layout of reprocessing plants, and the establishment of the reprocessing plant and disposal repository in order of priority.

(2) Present economic development and prospects at the preselected sites, and population density and distribution.

(3) Expense and benefit analysis. For example, selection of package materials and containers, consideration of transportation conditions and estimation of costs, etc.

(4) Decisions made by environmental protection agencies of the government.

(5) Attitude of local administrative departments.

(6) Design, construction, and management of the disposal repository, and guarantees after decommissioning.

The natural conditions are as follows:

(1) Geographic Location and Transportation Conditions.
For a selected area, these should be as near to the radioactive waste source area as possible. Climatic conditions in the selected area are considered, such as type and quantity of precipitation, evaporation, direction and intensity of wind, snowfall, and freezing. These factors affect the denudation of the land surface, the occurrence of surface and groundwater, and leaching and migration of radioactive nuclides

(2) Topographic and Geomorphologic Conditions.
Topographic variations and geomorphologic features may have an effect on the development and distribution of the river system, the change of hydrogeological conditions, the infiltration of precipitation and the fluctuation of groundwater table. Engineering, transportation and construction, and the possibility of accidents in waste transportation are additional factors that should be taken into account.

(3) Conditions of Geology and Properties of Rocks and Minerals.
Safety in the processing of radioactive wastes depends on artificial shielding of the storage vault and natural shielding of the geological body. Natural shielding aims at preventing the contact between groundwater and radioactive wastes, absorbing radioactive elements and retarding radioactive nuclide migration. Studies should be conducted on spatial distribution and age of the rock mass, depth and geologic structure of the burial zones, including thickness, size, constitution, unconformity, homogeneity, underlying lateral and overlying strata. In addition, mineral composition plays an effective role in the chemical reaction between radioactive wastes and rocks, and controls the chemical processes in groundwater. Geologically, the most important basis for site selection is provided by adsorption, retardation, delay and dissolution of constituent materials in the strata. The physical and chemical properties of the rocks, such as structural character, adsorption, permeability, porosity, solubility, diffusion, fluid inclusions and physico-mechanical properties, have a decisive influence on radioactive nuclide migration, shielding effect and engineering construction.

(4) Geological Structure and Seismic-Geologic Conditions
Theoretically, the selected areas should be those with geologic structures as simple as possible and those of regional stability without seismic activities. This is because such structures control the runoff of water, and the direction and rate of nuclide migration. Tectonic activities often lead to earthquakes, upheaving and subsidence of the land surface, and sedimentation and denudation. Earthquakes may harm the project through changes brought on by the collapse of the shielding structure, changes in the state of surface and groundwater, and an increase in the upward migration velocity of nuclides towards the surface. Therefore, geotectonics, geological structures and seismic activities in preselected areas should be studied, particularly the dip angle and strike of the strata, the development of faults, folds, fissures and joints and the history of regional geologic development.

(5) Hydrogeological Conditions
Surface and groundwater movement may induce the radioactive nuclides to migrate and enter the biosphere. Thus, studies should emphasize such aspects as the development, distribution and evolution of water systems, the underlying aquifer and its recharge and discharge areas, the path of groundwater movement and the chemical reactions between groundwater and rock formations. Also meaningful is the study of the confining beds over the aquifers, variation of water pressures and flows, fluctuations in the water table, relations between groundwater and the surface and chemical properties of the aquifers, the connection between the geochemical behavior of the saturated and unsaturated zones, and the seasonal variation of soil temperature.

(6) Engineering Geological Conditions
Geological conditions favorable for engineering construction should be studied in the site selection phase and will involve

rock mechanics, excavation conditions, mechanical support and geostress as well. Other items of investigation should include the problems of heat conduction, magnetism, electrical conductivity, plasticity, dynamic characteristics and fracturing. In addition to the general problem of rock stability, there are also questions on stability of the vaults after excavation, thermomechanical stability, dynamic stability and long-term stability of the wastes.

5.3. Specific Methods in Site Selection

Selecting sites for repositories of radioactive waste is a complicated and comprehensive multi-discipline type of research work. The process requires the application of remote sensing (aerial photos, radar displays, infrared scanning imagery), regional geology (field geological surveys, geologic mapping), geochemistry, petrology, mineralogy, tectonics, and hydrogeology. In the field of geophysics, one can use aerial geophysical surveys; electric, electromagnetic and seismic soundings; drilling logs (electric, neutron and acoustic); and television recordings and compilations, One also carries out laboratory analyses and experiments to accomplish synthetic geological investigations concerning economic, geographical (including population, communication and transportation, climate, etc.) and topographic and geomorphologic conditions. The geologic body and related properties of rocks and minerals, geologic structures and earthquakes, hydrogeologic and engineering geologic conditions are additional features.

The actual process of selection consists of a technical preparation phase and a geological investigation phase. The technical phase starts with a nation-wide general survey and then proceeds through regional selection and an areal reselection ending with a determination of the candidate area. The geologic study phase involves site selection, candidate site work, intensive site work, and final site work.

5.4. Preselected Area in Northwestern Part of Gansu Province

Since the Pre-Proterozoic era, the Gansu Province and its neighboring areas have been subjected to multiple tectonic activities. Tectonic features are extensively developed in different directions and on various scales. There are about 30 tectonic systems including gigantic latitudinal and meridional systems, epsilon-type, xi-type and rotational shear tectonic systems. There are also tectonic systems not yet included in categories, such as east-west and north-south regional tectonic belts, a northwest palaeotectonic belt, arc-shaped and northeast structures, and so on. These structures interpenetrate and intertransform each other, forming a very complicated tectonic strain picture.

The preselected area is located in the transitional zone in between the northwest tectonic belt of Qilian Mts., the east-west tectonic belt of the Beishan Mts. and the Alxa arc-shaped tectonic belt, i.e., at the western sector of the Hexi Corridor. Tectonically, this is an area of instability.

(1) The obvious geomorphological features that reflect the influence of the Dunhuang-Alxa east-west fracture belt on the Quaternary System indicate that tectonic movement is still active in the neoid period.

(2) In Gansu province, the Qi-Lu-He epsilon-type tectonic system is only part of the west flank of the Qi-Lu arc-shaped fold belt. On both flanks of the system, the neoid activities along the fold belts have been so intense as to induce strong earthquakes.

(3) The Hexi tectonic system is the major one in the selected area, with dominant neoid activities. Prior to the Teritiary, at least in the late stage of the Mesozoic era, the embryonic form of the system came into existence. The system was extremely active in the Cenozoic and was closely related with the distribution of earthquakes in recent time.

(4) Aeromagnetic surveys and satellite photos have revealed that concealed fractures exist on both sides of the Alxa arc-shaped tectonic belt in accord with the uplifted zones. The fracture belt on the southern boundary of both flanks of the front arc, where compressional phenomena are predominant, is still active at present, being one of the important earthquake-controlling structures.

Gansu Province is an area with earthquakes of high frequency and intensity, which is an area of the type that can be counted on one's fingers in China. The statistics of high seismic activities show that the number of earthquakes of magnitude 6 (Richter scale) that have taken place in Gansu province is in sixth place, next only to Taiwan, Yunnan, Tibet, Xinjiang and Sichuan. It is therefore evident that the study of seismic activities should be emphasized in site selection. Those nonnegligible factors such as stress concentration trends and earthquake magnitude should be analyzed and an areal division should be made.

Some earthquakes in Gansu Province are related to the neoid activities on the west flank of the Qi-Lu-He epsilon-type tectonic system. It is very important to study the pattern of the active tectonic belt in the neoid period and the relationship with seismic activities. During the study, geostress or earth stress and displacement crossing the faults should be measured, characteristics of seismic active zones studied, and the present tectonic stress field and earthquake endangered sector discussed.

In Gansu, earthquakes often happen on the transpositional composite position of the neoid mobile tectonic belt and Hexi neoid mobile tectonic belt. These localities must be excluded from consideration in site selection.

As the tectonic activities have been most violent in Gansu since the neoid period, the tectonic system has been rejuvenated to different extents under the influence of the regional stress field forming the neoid mobile tectonic belts. These tectonic belts were mostly developed on the basis of inheriting the original fractures of individual systems, accompanied by some newly formed tectonic traces.

The major patterns of mobility and forms of presentation of the neoid active tectonic structures include unconformities, the Neogene folds, the dipping occurrence of the Quaternary system, the rejuvenation of old faults, the appearance of new faults, the forming of faulted basins, magmatic activities of the Neogene, the long-term uplifting and denudation and the multiple terraces developed along river valleys.

According to analyses of geological structures, seismic activities and geomorphologic features, if the Lanzhou-Xinjiang railway running in the northwest direction be regarded as the boundary, the sites for radioactive waste disposal in the Gansu area should be located and expanded to the northeast of the boundary line along this railway. It is quite inappropriate to determine the locality of a disposal site southwest of the line where the Qilian Mts. extend and a series of faults develop and where the active seismic zone lies.

The candidate area in the northwest part of Gansu Province is an area of unstability. Nevertheless, some relatively stable sites can be found. Proposals for future site selection work in NW Gansu are as follows:

(1) Regionally, attention should be paid to the distribution and development of the neoid tectonic activities, the factors controlling seismic activities, the trend in stress concentrations, subdivisions into small areas according to seismic intensities and measurements of geostress or earth stress. A discussion should be made on the present tectonic stress field and seismic endangered sectors. Especially, the transpositional composite position between the neoid tectonic belt and the Hexi neoid mobile belt should be excluded from consideration in selecting a site.

(2) Faults definitely need to be studied using aerial infrared scanning, and shallow seismic prospecting should be conducted so as to obtain dynamic-elastic parameters. A shallow high-resolution digital seismograph can be used to carry out P-wave reflection seismic surveys. Geological mapping at the scale 1:50,000 may be done in favorable areas, if necessary, in order to make a further evaluation based on studies of lithological characters, faults and fissures of rock masses and deep geologic conditions.

5.5 Preselected Area in Central Inner Mongolia

Through comprehensive analyses of the regional geology and a comparison of geological structure, rock formation and economic geography, the central part of Inner Mongolia is considered tentatively an area of regional stability with relatively favorable engineering geological conditions.

(1) The area of regional stability has a low seismic intensity although small earthquakes that have occurred sporadically have caused some slight damage. The creep rate of concealed structures at depth is very slow.

(2) Engineering geology studies of the Mesozoic terrestrial clastic sedimentary rocks in the area reveal formations composed of (deep) considerably hard to (shallow and near surface) soft layered sandstones and mudstones. The cementing materials are mainly argillaceous and calcareous, and the rocks are low in permeability and highly varying in hardness but generally have a very high compressive strength.

(3) According to data from boreholes, the Mesozoic strata are composed of mudstone, siltstone and sandstone. Partial areas of Triassic strata have a thickness up to 800-1200 m because of the control of the paleorelief in the basement at the time of deposition. Siltstone or fine sandstone in

the middle segment of the upper Triassic series has a relatively low permeability and appropriate mechanical properties. The underlying mudstone of the middle and lower Triassic may serve as a confining bed and an absorbing-cushioning protective layer at the bottom of the repository. The overlying Jurassic red mudstone may serve as an effective barrier between the deeper groundwater within the Triassic system and the shallow interstratal groundwater within the Cretaceous.

(4) The preselected area borders on a boundless desert where the annual evaporation is far more than the precipitation and the absolute aridity is as high as 3.0. The most important factor is that there are several mudstone aquitards, which may basically eliminate the possibility of permeation and dissolution of shallow groundwater and meteoric water. The distribution and variation of groundwater in the area have fixed regularities, and the water for domestic use is of fairly good quality. Moreover, rivers in the middle and southern part of the area belong to the Ordos interior water system. Therefore, there is no possibility of contaminating the drainage system of the Yellow River, if the repository for nuclear wastes is constructed in the area.

(5) The preselected area is sparsely populated, economically undeveloped, and relatively backward in culture and education. The national economic output value of the area is rather low, and there are hardly any prospects for industry, commerce and tourism in this area. The area will not enjoy any priority in national economic development for a relatively long period into the future.

(6) The area has transport facilities, and more than 90 percent of the highways need no additional services for maintenance. However, the geographical location of the area is remote from the source of nuclear wastes; thus, the cost of transportation will be much higher.

(7) The central area of Inner Mongolia, through rich in coal resources, is short in the supply of electric power and petroleum products.

5.6. Preselected Area in Northwest Shaanxi Province

There are 305 complex rocks in this area belonging to a group of rock masses of complex composition (from ultrabasic to basic) and complicated occurrence (from epigenetic to plutonic), with repeated activities. The main body is a secondary instrusive plagioclase granite, with an outcrop area of about 1453 km^2.

Through comprehensive geologic, seismic and remote-sensing studies, it is considered preliminarily that this preselected area for a repository of nuclear wastes has several favorable conditions as follows:

(1) It is near a railroad, and the area is convenient for railway and highway traffic because of a low-mountain and hilly terrain.

(2) There is ample electric power supplied by the Liujia Gorge power station.

(3) The geologic, seismic and remote-sensing analyses indicate that the area is a long-term stable land block located on a gigantic batholith with undeveloped fissures, which meet the requirements for building deep underground engineering structures.

(4) There is a technical contingent that can be engaged in geological mapping, hydrogeological investigations, and geophysical and geochemical prospecting.

(5) There is no problem in evacuating the area which is sparsely populated and less cultivated.

(6) The geologic process has been very weak after forming of the rock mass. So far, deposits of potential mineral reserves have not been discovered in the area.

If further studies are necessary, the following aspects of work are suggested: 1 to 50,000 geologic mapping, observation and study on the regularities of faults and the development of fissures in rocks, geophysical and geochemical studies in part of the area, and an investigation of the deep geological conditions.

5.7. Preselected Area in Central Guangdong Province

The preselected area is characterized by the following factors.

(1) In its geologic development, the area is located in a long-term stable, upwarped zone, where there are fewer visible faults than in other areas of Guangdong Province, and faulting is less frequent.

(2) The area is located in a safe zone between the seismic safe section in northern Guangdong and the seismic structural section in central Guangdong.

(3) The area is relatively well populated.

(4) According to previous engineering data, the fissures become more and more tightly closed with increasing depth, with nearly no water. Thus, the geological system provides a favorable hydrogeological condition.

(5) The intact granitic rock has a high compressive and shear strength, which is favorable to the construction of a disposal repository and to prevent underground openings from collapsing.

In summary, by comparison with four other areas, the preselected site in central Guangdong is a rather ideal site for a disposal repository. However, in an overall consideration, there are disadvantages as follows: (1) The area is near the city of Guangzhou, which is a prospective planning area for future economic development. (2) There is a high rate of precipitation and runoff into the Zhujiang River system, which is one of the major water sources. As a result, pollution of the Zhujiang River is a factor that needs serious consideration. (3) At present, the designed transportation route for the Daya Gulf nuclear power station is by the sea. However, the cost of transporting nuclear wastes to the preselected area by land will be too high.

5.8. Preselected Area in Western Zhejiang Province

The western part of Zhejiang Province (including part of south Anhui) is one of the favorable preselected areas. Two sectors have been preselected in this area. The selection of each is based mainly on the following factors: geologic structure, seismic activity, regularity of neoid tectonic movement apart from the consideration of economic development, density of population and the nearby access to nuclear wastes from the Qinshan nuclear power station.

The selection is also based on the following:

(1) The area north of the Jiangshan-Shaoxing fault belongs to the west Zhejiang synclinorium, being folded intensely during the Indo-sinian movement, accompanied by some compression-shear fractures, including from west to east the Wuxing-Shunxi and Linan-Majin fracture belts. The former belt at the western end lies outside the selected area.

(2) In southeast Zhejiang, the Cathaysian structure was overlain and transformed, due to the violent Yanshanian movement and extensive volcanic eruptions and tectonic activities. According to data from aeromagnetic and gravity surveys and the study of volcano-tectonic activities, a basement structure exists under the volcanic rocks of the area with an axial direction of N50E. However, in west Zhejiang, the aeromagnetic survey reveals a negative magnetic field, characterizing a stable geologic environment.

(3) The Neocathaysian structure formed since the final stage of the middle Triassic epoch, the activity of which becomes gradually weakened from east to west, has led to the forming of Longyou-Qingyuan faulted zones in southeast Zhejiang. In eastern Zhejiang where tectonic activities were violent during the Himalayan stage, there occurred basic and ultrabasic intrusions. The neotectonic movement, which is an inheritance of old structures, exhibits intermittent uplifting, resulting in the formation of mountainous terraces and the development of river-valley terraces.

(4) The regional East-West structures are all far from the preselected area in the western part of Zhejiang.

(5) In northwestern Zhejiang, although the Cathaysian system is the trunk structure of the area, it was kept intact mainly within the Palaeozoic strata.

(6) Neocathaysian structures are not developed in northwestern Zhejiang and existing fractured structures are all far from the preselected area.

(7) The East-West structures in northwestern Zhejiang were formed in the Precambrian, developed and matured during the Xuefeng movement, and have been repeatedly active since the Mesozoic reaching a climax in the Himalayan stage. Nevertheless they are also far from the preselected area.

(8) The seismic activity in Zhejiang province is characterized by stages and zones, mostly concentrated in the north Zhejiang plain and in the Linhai-Wenzhou and Sheng Xian-Qingyuan zones in east Zhejiang.

(9) The migration of seismic activities is mainly in the NE direction in northwest Zhejiang.

(10) According to the characteristics of the stress field in the active structures, the major seismic-inducing fracture belt is comprised of the neoid structures in the east part in the fault zones of: Xiaoshan-Qiuchuan, Shangyu-Lishui and Zhenhai-Wenzhou.

(11) The main seismic zones of Jiaxing-Changshan, Lishui-Qingyuan and Dinghai-Wenzhou, and the main seismic endangered areas of Hangjia Lake, Zhenhai-Dinghai, Hexi-Qingyuan and Leqing-Wenzhou are all concentrated in the eastern part of Zhejiang province.

According to preliminary analyses of the available data, 866 preselected areas can be reselected as disposal sites for low- and intermediate-level radioactive wastes. The favorable conditions are as follows:

(1) Favorable lithologic characteristics. The strata of the area are mainly vitric tuff and sedimentary tuff in the second layer of the Jurassic Guangde Formation. Bentonite was formed after the hydrolysis and devitrification of this vitric tuff. Bentonite has a high adsorptive capacity for radioactive nuclides, and has been widely accepted as backfilling and shielding material in nuclear waste disposal. The wide distribution of bentonite may be considered as disposal sites for low-level and intermediate-level radioactive wastes. These deposits may be used as either the terrain in which to dispose of nuclear wastes or as a good source of backfilling and shielding material. In addition, the surrounding sections in the bentonite deposit, where the content of quartz is relatively high, may provide additives of quartz sand for the backfilling material. Simultaneously, they may also serve as disposal sites for nuclear wastes in those segments below the standards set for quartz exploitation.

(2) Simple geological structures and no earthquakes.

(3) Simple hydrogeological conditions. There are no rivers and rarely any perennial springs.

(4) Sparsely populated, no large villages because of a shortage in water resources.

(5) Favorable landform, barren and hilly.

(6) Convenient access to the Qinshan nuclear power plant.

(7) A complete set of industrial facilities several kilometers from the area, such as a cement plant, brickfield, coal mine, thermal power plant, etc.

(8) Obvious economic benefits. As the area is near the Qinshan nuclear power plant, if the low- and intermediate-level wastes can be disposed of directly after the process of cement solidification, the construction of a storehouse and temporary storage may be excluded so as to save a great amount of money.

On the basis of the preliminary and comprehensive analyses, 67 granodioritic rock masses in south Anhui can be considered as preselected sites for high-level nuclear waste disposal. The conditions are favorable as follows:

(1) The area is located in the mountains where there are transport facilities with a sparse population.

(2) Excellent granitic rocks form a batholith of considerable size with a total area of outcrops of more than 300 square kilometers. According to foreign data, granite is the target rock of disposal sites in most countries for high-level radioactive wastes.

(3) The structure of faults and fissures is simple at the central part of the rock mass, and the vertical and lateral fissures are less developed, which is unfavorable for the migration of nuclides. From the point of environmental safety, it is a more suitable disposal site.

5.9. Conclusions

In the geologic disposal of radioactive wastes, the selection of the site is an important effort. It takes a fairly long period, say 10-20 years, for all phases including field investigations, in-situ experiments and exploration, site selection, demonstration and verification, and final approval. Comparison and reevaluation are usually needed among a number of preselected sites. Apart from the preselected areas described above, site selection work will be further expanded to other provinces or regions, such as in the northeast China, Xinjiang, Qinghai, Jinagxi, Anhui, Fujian, and Guanxi.

As a result of the geological studies and evaluations of preselected sites that have been made, it is concluded that the disposal of radioactive wastes in China is feasible.

Chapter 6

Geological Disposal of Radioactive Wastes in Finland

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6.1. Introduction

The Finnish power utilities operate four nuclear power plants. Teollisuuden Voima Oy (TVO) has two units, TVO I and II (BWRs, 2 × 710 MWe), at Olkiluoto, Eurajoki, and Imatran Voima Oy (IVO) has two units, Lo 1 and 2 (PWRs, 2 × 445 MWe), at Loviisa. These plants produce about 30% of the electricity consumed in Finland.

The waste producer in Finland is responsible for the safe management of radioactive wastes. The objectives and schedules of the waste management program were set forth in 1983 in a policy decision of the Government. The Ministry of Trade and Industry and the Finnish Center for Radiation and Nuclear Safety supervise the progress of the program. Each calendar year, a plan for waste management and research work is presented to the authorities.

The main part of the research work carried out in Finland is financed by the utility companies. Cooperation between TVO and IVO is coordinated by the joint Nuclear Waste Commission. Research institutes, universities and consulting companies participate as contractors in the research program of the utilities. The research budget for the year 1989 was FIM 39 million (1 FIM = $0.23 US). In order to maintain independent expertise, the Ministry also finances its own research program in the field of waste management; and in 1989, the budget was FIM 6 million.

6.2. Waste Amounts

TVO I was commissioned in 1978 and TVO II, in 1980. By the end of 1989, the total power production was about 103 TWh. By 1989, the reactors had generated 410 tU of spent fuel and 1,700 m^3 (conditioned waste volume) of low- and intermediate-level wastes (LLW/ILW). The estimated minimum lifetime of the reactors is 40 years. The estimated total amounts of waste from the two units at Olkiluoto after 40 years of operations are as follows: 1,840 tU of spent fuel, 8,000 m^3 of operating LLW/ILW and 25,000-30,000 m^3 of decommissioned wastes.

Lo 1 was commissioned in 1977, and Lo 2, in 1980. By the end of 1989, the total power production was about 70 TWh. The two reactors generate 28 tU of spent fuel annually. The amount of LLW/ILW at the end of 1989 was 1,500 m^3 (volume of unconditioned liquid and compressed dry wastes). The estimated total amount of LLW/ILW at Loviisa after 30 years operations of two units is as follows: 2,500-5,500 m^3 of low- and intermediate-level wastes depending on the method of treatment employed and 13,000 m^3 of decommissioned wastes.

6.3. Repositories for LLW/ILW

At Olkiluoto the low- and intermediate-level wastes are conditioned and stored at the power plant site, and the final repository for these wastes is being constructed at the same site. Dry wastes from maintenance work are compressed and packed in 200 liter drums. Spent ion-exchange resins are bituminized, and waste packages are stored in waste process buildings at the power plant and in two interim storage buildings.

Construction of the final repository for LLW/ILW (VLJ repository) in crystalline bedrock at Olkiluoto started in the spring of 1988. The excavation work was completed in the summer of 1989, and construction and installation work will proceed so that the repository can be commissioned in 1992. Waste drums will be emplaced in two silos at a depth of 70-100 m as shown in Figure 6.1. The silos will have a total capacity of 40,000 drums. The total excavated rock volume of silos, crane hall, tunnels and shaft is 90,000 m^3.

At Loviisa LLW/ILW wastes are also conditioned and stored at the plant site. Wet wastes (ion-exchange resins, evaporater concentrates) are stored for the time being in liquid form in a tank storage facility. Dry wastes from maintenance work are compressed and packed in 200 liter drums. New treatment procedures, such as microbiological treatment and cesium separation, are under development.

IVO will construct its own final repository for the Loviisa LLW/ILW wastes in the bedrock at the plant site. It will be constructed at the end of the 1990's at the earliest, as there is still much unused storage capacity at the power plant site.

6.4. Spent Fuel Management

IVO returns spent fuel from the Loviisa power plant to the Soviet fuel supplier. Fuel bundles are stored for five years at the plant before being transported to the Soviet Union. No wastes will be returned to Finland.

A separate interim storage facility (KPA storage) has been constructed for TVO's spent fuel at the Olkiluoto plant site. This operation started in 1987, and there are three storage pools in the facility having a total capacity of 1,200 tU. Expansion of the facility is possible.

The alternatives for TVO's spent fuel management after the interim storage phase are:

(1) direct disposal of spent fuel in Finland,

(2) foreign reprocessing and return of wastes to TVO, and

(3) foreign reprocessing including waste disposal, or foreign direct disposal service.

So far, no agreements have been signed for foreign services. Preparations are underway for direct final disposal of spent fuel in a bedrock site in Finland. The present program comprises site selection studies, development and optimization of the repository concept and safety studies. A repository is planned to be constructed in the 2010's and to be commissioned by the year 2020.

6.5. Site Selection

A site for the final repository to contain TVO's spent fuel will be selected by the year 2000. As the first stage in the site investigations, an analysis was made during 1983-85 to locate possible areas for field investigations. On the basis of structural analyses, 327 bedrock blocks, each about 100 km^2 in area, were first selected for further investigation of different geological and environmental factors. This study resulted in the selection in 1985 of 102 potential areas each 5-10 km^2 in area. The results were reviewed by authorities in 1986.

TVO selected five areas for field investigation in April 1987. These are located in the Kuhmo, Hyrynsalmi, Konginkangas, Sievi and Eurajoki communities (Figure 6.2). The program consists of airborne surveys, shallow and deep drilling, and measurements and sampling from the surface as well as in boreholes. Field work is followed by laboratory studies in addition to modelling and evaluation activities.

Geological mapping and geophysical surveys (airborne, surficial) have been carried out at all five sites. Deep boreholes with a diameter of 56 mm have been completed at four sites, and drilling at Eurajoki will be continued in 1990. A comprehensive geophysical logging program has been carried out including fluid logs; resistivity, radiometric, acoustic and tube wave logs; and borehole radar and VSP measurements.

Hydraulic conductivity has been measured in cored holes; the measurements were made using TVO's multihose equipment and the constant head injection method. The groundwater table is being measured in shallow standpipes drilled through the soil layers to bedrock. Near the surface, head distributions are being measured in multilevel piezometers at four levels ranging from the surface to a depth of 100 m.

The cored boreholes have been drilled with a larger diameter to a depth of 40 m. This provides the advantage of being able to install the packer system for head monitoring or the pump/packer system for test pumping. Monitoring of hydraulic heads has begun at the Kuhmo site.

Groundwater samples have been collected in the deep boreholes. Labelled drilling fluids exist in varying amounts in fractures near the boreholes. Saline waters have been encountered in the Sievi area below 600 m, and the highest chloride content has been 6,000-7,000 mg/l.

The suitability of the site candidates for final disposal of spent fuel will be evaluated preliminarily in 1992, after which the two or three most suitable sites will be investigated and assessed in detail during the period 1993-2000. The final site is to be selected by the end of 2000. Complimentary investigations will be continued between 2001-2010.

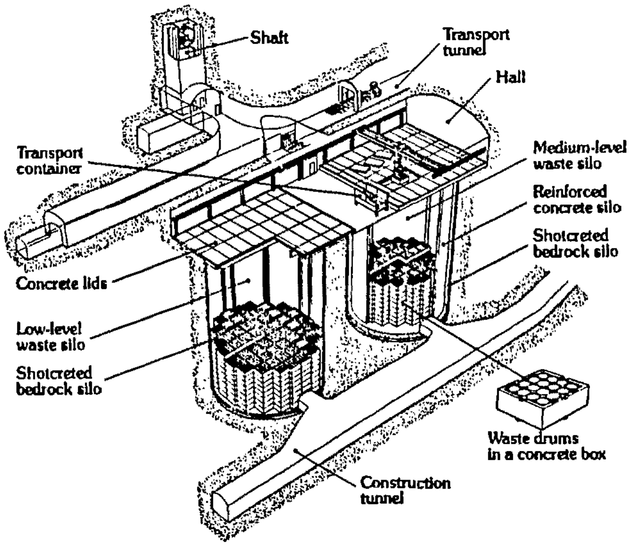

Figure 6.1. The final repository for LLW/ILW at Olkiluoto is under construction in bedrock at the plant site. Waste drums will be emplaced in the two silos at a depth of 70-100 m.

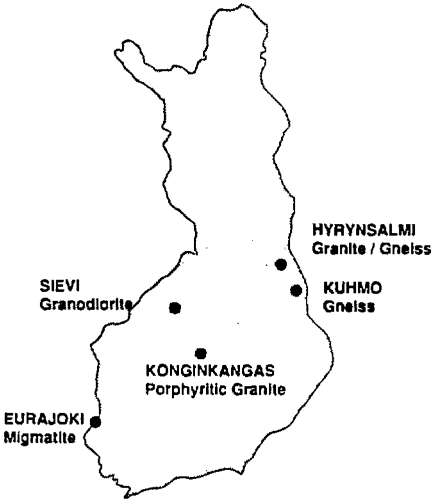

Figure 6.2. Locations of five candidate areas where TVO is carrying out deep drilling and other rock investigations. The site for a final repository is to be selected by the year 2000.

6.6. Modelling Investigations

The modelling of each area is carried out in two steps consisting of a bedrock structure model and a groundwater flow model. A preliminary model has been made for the Kuhmo site, and modelling of the Hyrynsalmi site is in progress. A 3-dimensional CAD-system has been developed and is now being used to make the illustration of results and modelling easier.

The bedrock model for an area contains the geometry of the rock types and the network of fractured zones. Typically, the model for an area forms a bedrock block. The block itself is surrounded by major fracture zones, usually apparent as topographic depressions on the maps and revealed as geophysical anomalies in the field measurements.

The groundwater modelling is concentrated on investigations of flows inside the block. Boundary conditions are determined by the surrounding zones. A 3-D mesh of elements is used for groundwater flow analysis, and the model is based on the porous media approach. The primary input parameters are contours of the groundwater table and hydraulic conductivities of the different zones.

The element mesh employed in the analysis of the preliminary modelling phase at the Kuhmo site covers an area of 2.3 km x 2.0 km, and the depth of the model is 2 km. The area is bounded by major fracture zones. The calculated heads will be compared with measured heads in future work.

6.7. Development of Encapsulation and Repository

The concept for a repository to hold spent fuel from TVO was presented to the authorities in 1985. It consists of horizontal tunnels at a depth of several hundred meters in crystalline bedrock. Vertical holes will be drilled in the floors of drifts, and each hole will hold one copper canister that is isolated from the rock by a layer of bentonite. An encapsulation plant will be located at the repository site and will be connected to the underground works via vertical shafts.

The development of technical plans is aimed at more economical solutions with a high safety level. The program has the following objectives:

(1) cold encapsulation process, in which the space between the canister and fuel bundles is filled with solid grains instead of molten metal,

(2) selection of material and structure for canister, and

(3) feasibility of bentonite granulates instead of highly compacted bentonite blocks, as buffer material.

6.8. Safety of Final Disposal

A comprehensive safety assessment showing that spent fuel can be safely disposed of in the Finnish bedrock was reported at the end of 1985. Work on applied calculation models and data input has continued, e.g. the development of near-field and migration models, experimental laboratory studies on leaching of uranium, corrosion of canister materials, diffusion in buffer materials, and sorption of radionuclides in fractures. In 1992, an updated safety assessment will be reported, in which the bedrock investigations from different sites will be taken into account.

6.9. Decommissioning Studies

Decommissioning plans for the power plant units are updated at intervals of five years. The plan for the Loviisa power plant reported in 1987 was based on the following assumptions:

(1) dismantling to start immediately after end of operations,

(2) no segmenting of pressure vessels,

(3) final disposal of wastes in bedrock at the plant site using the same repository developed for LLW/ILW.

The preliminary plan in 1987 for TVO was based on the following assumptions:

(1) cooling period of 30 years between the end of operations and the start of dismantling,

(2) segmenting of pressure vessels,

(3) final disposal of wastes in bedrock at the plant site using an extension of the VLJ repository, and

(4) final disposal of activated core components from the operating period in same repository.

6.10. Funding Arrangements

The utilities in Finland provide the monies for future costs of nuclear waste management. An updated cost estimate that includes spent fuel, low- and intermediate-level wastes, and decommissioning has to be prepared annually. This estimate includes the future costs for the management of the waste already produced. Based on these estimates, the Ministry of Trade and Industry confirms the fee to be paid each year into a government controlled fund.

The present estimate for TVO's waste management is FIM 4,000 million. The main components are the costs for final disposal of spent fuel and decommissioning of TVO I and II. By 1989, TVO had paid FIM 1,500 million into the fund. The estimate for IVO's waste management is FIM 1,000 million and consists mainly of the costs of decommissioning Lo 1 and 2 and constructing the final repository for LLW. By 1989, IVO had paid FIM 395 million into the fund.

6.11. Information Activities

In addition to the licenses required by the government and the authorities, acceptance by the local community is also needed for the construction of a nuclear waste facility in Finland. The government asks for local approval before the construction of a repository can commence.

The greatest need for information on activities has arisen in connection with the site selection investigations for a spent fuel repository. For the field studies to begin, only a landowner's permit is required. However, cooperation with the communities involved has become important when field work is to be carried out. Five separate cooperation groups have been organized between TVO and each community where investigations are to be undertaken. Several meetings with each group have been arranged annually. In these meetings, information on progress and the results of investigations have been presented to the members, the need for information activities is discussed, the use of local services is reviewed, etc.

The public is informed of the site investigations and the waste management program both directly and through the media. Open houses have been arranged at drill sites and at the local offices of TVO. Lectures on waste management have been given to interested groups such as local councils, teachers, clubs, etc.

Chapter 7

The French Radioactive Waste Management Program

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7.1. Introduction

Long term industrial management of radioactive waste in France is carried out by Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), which was created within C.E.A. in 1979 by an interministerial order. ANDRA is responsible mainly for design, siting, construction, and operation of the disposal centers for every kind of waste produced in the country. Furthermore, ANDRA has to define and control the required quality of the waste packages that are prepared for disposal. In other words, ANDRA has to establish the specifications for waste packages that the producers must follow so that their packages can be accepted for ultimate disposal.

As far as disposal is concerned, wastes are classified in two categories. The first category includes all of the so-called "short-lived" waste mainly containing radioactive substances with a half-life less than 30 years (beta/gamma emitters) and, in a few cases, a very small amount of long half-life substances. Most of these wastes are produced during the operation of nuclear reactors, e.g. resins and filters for purifying cooling water systems. The remainder comes from the normal operation of fuel cycle plants, large research laboratories, and various users of radioactive sources, such as hospitals, universities, industries, etc. The first waste category accounts for nearly 90% by volume of the total amount of radioactive waste but contains only 1% of the total activity. In France, the technical option for final disposal is in near surface repositories.

The second category includes the waste containing a significant amount of long-lived substances such as the transuranic nuclides. The radioactive substances found in this category come from irradiated reactor fuel rods, whether the rods are reprocessed or not. When spent fuel is reprocessed, it is possible to identify two subcategories:

(1) alpha waste, from the name of their principle long-lived nuclides. These wastes have a low to medium activity level and a low thermal release,

(2) vitrified waste, from the name of the conditioning process which, in addition to the long-lived nuclides, contains a large amount of heat that decreases with time accor .ng to the half lives of cesium-137 and strontium-90 (30 years).

In France, the technical option for final disposal of this waste category is a continental deep underground repository.

7.2. Surface Disposal

ANDRA has developed an original concept for surface disposal, often referred to as "earth mounded concrete structures", which provides full isolation of the waste from the human environment. This concept provides isolation under controlled conditions and for a period of time long enough to allow the radioactivity to decay to a level that is acceptable for returning the site to unrestricted use afterwards. This concept has been progressively implemented since 1969, at Centre de la Manche, the first French repository, and has been chosen for the second disposal center at Centre de l'Aube, now under construction.

7.2.1. Centre de la Manche

Centre de la Manche has been in operation for 20 years on a 30-acre tract of land at the tip of the Contentin peninsula near the town of Cherbourg. According to the radioactive content, the type of conditioning matrix, and the characteristics of the container, waste packages are piled directly on concrete pads or placed in cubic modules of reinforced concrete that are backfilled with concrete. A sophisticated cover made of watertight artificial and natural materials protects the structure from infiltration by rainwater. The base of the storage area is provided with an underground gravity drainage system to collect and monitor any possible infiltration of water through the modules.

Each waste package disposed of in the repository is recorded. Its main characteristics and final location will be stored in different places for several hundred years, corresponding to the institutional control period. This permanent inventory of the activity contained within the waste is regularly updated.

Centre de la Manche has a total capacity of about 17 million ft^3 of waste packages. According to the present rate of deliveries, it will be filled in the early 90's. Thus, after examining ANDRA proposals, the French Government ordered the creation of a second new repository.

7.2.2. Centre de l'Aube

The decision to construct a second facility for disposal of short-lived waste was publicly announced by the Secretary of State for Energy on June 19, 1984, following approval by the government of the national radioactive waste management program prepared by ANDRA. In October of 1984, the site selection phase began in the Departments of Aube and Indre, then in the Department of Vienne, all of which, according to a site screening process, are located in geologically favorable areas. A second phase of the work was carried out only at Aube, and the relevant public inquiry was conducted from September 29 to November 10, 1986.

A Declaration of Public Utility for the project was signed by the Prime Minister on July 22, 1987, allowing ANDRA to purchase the necessary land. A construction permit was obtained October 11, 1988, and general earthwork began immediately. Complete licensing is expected in the summer of 1989.

The Centre de Stockage de l'Aube (CSA) is located 120 miles directly east of Paris, 33 miles beyond the town of Troyes, in champagne country. Brienne-le-Château, the terminal railway station, is eight miles from the repository. This site has a nominal capacity of 35 million ft^3. The size and characteristics of the required equipment were determined on the basis of waste package delivery forecasts established by the waste generators. On the basis of an annual delivered volume of 1.2 million ft^3, the operating period is on the order of 30 years.

Wastes that are delivered in a package form already approved by ANDRA satisfy the acceptance criteria imposed for surface disposal of radioactive material. They are transported in packages that conform to the national regulation for the transportation of hazardous material, class 7B. Each package bears a label that allows it to be identified and recorded by computer methods.

The design of CSA was developed in accordance with the recommendations set forth in the Fundamental Safety Rule No. 1.2, decreed by the Ministry of Industry. Site construction meets the quality assurance requirements stipulated in a ruling of August 10, 1984, and other relevant documents. The technical options incorporated in this design result from 20 years of operations at Centre de la Manche and can be summarized as follows:

(1) isolation of waste in strong concrete structures built above the highest level of the groundwater table,

(2) protection of the waste against rainwater using a watertight cover of artificial and natural materials,

(3) monitoring and collection of any water that infiltrates the disposal site, and

(4) protection of operating structures from extraneous waters under mobile covers until modules are filled and a preliminary cover is in place.

Waste isolation is provided by a combination of measures that prevent water from reaching the waste under normal operating conditions. In the event of accidental infiltration, these are designed to limit the quantity of radioactive products in the waters to a level that is sufficiently low so that any radiological consequences are negligible. By carefully selecting the location of the disposal facility, it has been possible to place it outside potential flood areas and above the highest water table.

To insure the integrity of the waste isolation system during the institutional control period, ANDRA has established certain criteria for each of the barriers of which the system is composed, i.e., the waste packages, the disposal units with the disposal caps, and the water collection system. The reliability of each component of this system (waste package, disposal alveole, platform, cap, pad and water collection system) is provided by the establishment of quality assurance procedures at the facilities of the waste generators. In addition, reliability is provided at each step of the program (design and construction of disposal structures), and for the duration of the first two phases of the disposal facility operation.

In order that system reliability be maintained after a seismic event, the following preventive measures are taken during the design phase:

(1) the site is placed in a region of low seismicity, i.e., a region where current knowledge of earth sciences indicates that a seismic event of high intensity has a low probability of occurrence over the next 300 years,

(2) The construction of the disposal structure must be based on parasceismic standards that are consistent with the characteristics of the selected site.

In terms of safety, the site must contain an additional guarantee of adequate isolation of the waste from water, which is the only foreseeable medium for the transfer of radioactivity during the institutional control period. The site must therefore contain certain hydrogeologic and geochemical properties that will enable it to mitigate potential failures of one of the barriers of the waste isolation system by "controlling" the release of radionuclides into the surrounding soil. The site must also feature hydrogeologic characteristics that are relatively simple and capable of being modelled for safety analysis purposes.

7.3. Deep Underground Disposal

Research on the treatment and conditioning of the second category of long-lived radioactive waste started in France more than 25 years ago, and these techniques have now been implemented industrially. High level wastes are and will be vitrified, and the transuranic wastes will be embedded in concrete or bitumen. The problem remaining to be solved for this second category is the problem of final disposal, as now exists for the short-lived wastes at Centre de la Manche.

As indicated earlier, the technical option is to develop isolation from the environment deep underground in a carefully selected geologic setting that can provide a very impervious rock type and long term stability over 10,000 years. Thus, the choice of the site is a key issue both for technical reasons and also with respect to the sociopolitical impact.

7.3.1. Site Selection Criteria

In view of the broad range of possible host rocks in France, it was decided to investigate the possibility of creating an underground repository in several different rock types. These include sedimentary rocks, such as clay or salt, and hard rocks, such as granite or schist. Each of these has particular advantages, and it has been demonstrated in different countries that a safe repository can be probably be constructed in each rock type. The possibility of having suitable sites in several host rocks provides an interesting flexibility for the final choice.

The first step in the site selection process was to compile a national inventory of the possible sites, based on a set of criteria among which long term stability and a favorable hydrogeologic setting were most important.

- Stability

  The selected site must be located in an area where no evidence of recent deformations has been clearly identified, so that possible changes in present conditions due to geologic events (glaciation, vertical movements, faulting, earthquakes) are acceptable with regard to safety of the repository. Such events must be estimated for each site with reference to the present, the recent past (historical events), and the Quaternary or late Pliocene period. Analytical methods can be used to estimate the typical parameters, their possible variations and their impact on the site. At this stage, it will be necessary to consider the regional geological environment.

- Hydrogeology

  Groundwater movement being the principal mechanism for radionuclide migration and transport to man's environment, it is essential that the volumes of water and the flowrates be as low as possible. Consequently, this requirement involves a host rock of low permeability and a low regional hydraulic gradient. Knowledge of the regional hydrogeology is essential. In addition, the local and regional surface water systems must be included in order to develop mathematical models to simulate and then predict the structure and behavior of the aquifers.

  Other criteria that play an important role in the site selection process include the mechanical properties of the host rock and cover rocks, the geochemical properties of the geological barrier, the acceptance of a minimum depth, and the thermal properties of the rock formations involved.

The national inventory was completed at the end of 1983. About 30 areas involving the four main rock types: clay, outcropping granite, schist and salt, were identified as possible locations for a future repository. In some cases, a combination of layers of different rock materials improves the isolation capacity of the site. Among the 30 areas, a preselection of four sites has been made that may warrant further field investigation.

7.3.2. Confirmation of Preselected Areas

Following authorization from the French Government, field exploration work is now being conducted '~ confirm the choice of the preselected areas. These areas are located in the following districts:

- Aisne, in the northeast part of the country, where the host rock includes two layers of argillaceous formations of Jurassic age. Each layer is more than 100 m thick, and they lie at depths between 400 and 750 m,
- Deux-Sèvres, in the central west, corresponds to a large outcrop of a granitic massif covering an area of 250 km^2 with a depth of more than 3,000 m,
- Maine-et-Loire, in the west, contains a Brioverien argillaceous schist located in the center of a 10 km large anticline. The schistose formation is more than 600 m thick, and
- Ain, in the central east, where Oligocene bedded salt is protected above and below by thick layers of argillaceous formations.

The general objectives of the site assessment program are to verify the general hypotheses which concern:

(1) geometry and homogeneity of the geological formations,
(2) location of discontinuities,
(3) relations between deep and shallow groundwaters,
(4) recent movements observed within surface deposits, and
(5) first analysis of the feasibility of the repository in the selected geological formation.

The field investigations naturally depend on the type of geological formation under investigation, but in all cases, they involve geophysical measurements from the surface, several deep boreholes with cores being taken, and a large number of laboratory and in situ tests. All of these investigations improve one's knowledge of the formations at depth (fracture patterns, hydrogeological characteristics, mechanical and thermal properties, nuclide retardation factors) and allow one to develop a preliminary assessment of the long term natural evolution of the site.

The confirmation program in the four districts started in 1987, and the first half of the year was devoted to public information programs. ANDRA installed local ''Missions'' on each site and placed them in charge not only of the technical aspects of the exploration programs, but also of the information to be provided to the communities involved, their elected officials, various government services, a variety of public groups and associations, and in particular, the public at large. Many brochures and documents were distributed in support of this effort.

Field exploration in the four areas began in the middle of 1987 with a program of geophysical investigations. Borehole drilling will be implemented later on; the first deep borehole in each area is planned for the end of 1989. The geophysical techniques employed have differed at each site as follows:

- Aisne (Clay). The first year was devoted to a high resolution vibroscis survey to define the structure of the two clay levels and locate potential faults. This effort terminated in January 1988 and used 150 km of profiles and 250 boreholes, approximately 100 m deep, for calibration purposes. A deep exploration hole was started in the Spring of 1989.
- Deux-Sèvres (Granite). Field measurements were limited to aerial exploration using spectroradiometry. A program of electic and magnetic geophysical studies will be performed later.
- Maine-et-Loire (Schist). Thirteen kilometers of electical resistivity lines were surveyed, and an aerial investigation was used to record 1,500 km of profiles while magnetic, electric and very low frequency (VLF) wave measurements were being made.
- Ain (Salt). A gravity survey has been completed, and a few reflection seismic profiles are still to be made.

This confirmation program is supposed to take about three to four years. The work to be performed naturally depends on the type of formation under investigation, but each site will require geophysical surveys at the surface and deep boreholes with core recovery. It is anticipated that this second phase will be completed by 1991.

7.3.3. Site Validation

At the end of the confirmation process, one site out of the four will be selected as the candidate for construction of an Underground Site Validation Laboratory (USVL). After a site has been selected, construction of the USVL will start. The laboratory will be the main tool to complete the selection process and validate the site. Validation means that using the data collected during this phase, it will be possible to demonstrate the technical feasibility and the economics of the repository. It will also be necessary to prepare a preliminary safety report to show that the consequences of the future operation of the repository are acceptable.

To achieve this goal, it will be necessary to explore in depth the whole rock volume of the repository and to carry out in situ experiments to confirm the thermal and mechanical behavior of the host rock. Furthermore, it will be necessary to evaluate and model the isolation capability of the whole system of barriers, including the backfill material and the different layers of the geosphere.

7.3.4. Construction of the Repository

The first priority in building the deep underground repository is to start with a facility for TRU waste, because there is a real economic incentive to dispose of such wastes as soon as possible. The heat they produce is low and does not necessitate a significant decay period. A series of possible configurations for the repository are under study in order to allow an early disposal of these wastes. The objective is to have the first waste packages accepted for final disposal shortly after 2000.

As far as HLW is concerned, the heat output will certainly make it necessary to allow this waste to decay for several decades in air-cooled storage facilities at the surface. The cooling time depends on the type of host rock involved in the repository, but it seems that 30 years of decay at the surface will be sufficient to allow the repository to operate satisfactorily. It seems very likely that no high-level waste will be disposed of underground in France until the year 2010.

Chapter 8

The Salt Dome of Gorleben - Target Site for the German Radioactive Waste Repository

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8.1. General Review of Activities

8.1.1. Responsibilities

Management of nuclear waste in the Federal Republic of Germany is regulated by the Atomic Energy Act. As this waste remains hazardous over a long period of time, the legislature considers its safe disposal to be a task incumbent upon the Federal Government. Until 1989, the Physikalisch-Technische Bundesanstalt (PTB, Federal Institute of Physics and Meterology), which is a federal authority, was entrusted with the responsibility for the construction and operation of installations for the long-term storage and disposal of nuclear waste. As of 1989, these responsibilities were transferred to the Bundesamt für Strahlenschutz (BfS, Federal Office for Radiation Protection). In performing its duties, the PTB may make use of "third parties." For this purpose, the Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE, German Company for the Construction and Operation of Waste Repositories) was founded.

The Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) acting as the Federal Geological Survey cooperates with BfS in performing geological, hydrogeological and geotechnical investigations for repository sites. These investigations include site characterization, geomechanical modelling, and geoscientific evaluation of geological barriers. The Institut für Tieflagerung (IfT, Institute for Deep Storage) in Brunswik forms part of the GSF research center in Munich and is the most important research institute in the area of responsibility.

The PTB is supervised in the field by the Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit (BMU, Federal Minister of the Environment, Nature Protection and Reactor Safety). BMU is responsible for all aspects of radioactive waste management. This ministry acts jointly with the Bundesminister für Forschung und Technologie (BMFT, Federal Minister for Research and Technology) for those aspects relating to research and technology in the field of long-term storage and disposal of nuclear waste.

8.1.2. Status of Waste Repositories

Several sites or activities with respect to radioactive waste disposal exist in the Federal Republic of Germany; an overview is given below (Merz et al., 1986; Closs and Papp, 1988).

8.1.2.1. Underground Laboratory Asse Salt Mine

- Location: Remlingen, State of Lower Saxony.
- R&D laboratory for the development and testing of disposal techniques.

- In operation since 1965; various disposal techniques for LLW and MLW were demonstrated during 1967-68.
- Borehole disposal experiments for HLW and MLW containers with retrievable emplacement of waste are in preparation.

Experimental programs on mining geology, hydrology, rock mechanics, heat transfer, geothermal behavior, near and far field phenomena, and backfilling and sealing are under way, as well as investigations on radiation stability, brine migration tests and radionuclide migration.

From 1983 to 1985, radioactive sources consisting of Co-60 have been used in the Asse mine to investigate the influence of both heat and radiation on rock salt. The results from the so-called "Brine Migration Test", a bilateral U.S. - German project, agreed closely with predicted values. This test was also the link between a number of electric heater tests performed earlier and the planned HLW disposal test.

The whole technical system for transportation, handling and emplacement of HLW canisters will be investigated in a large-scale demonstration test of HLW disposal in boreholes. Moreover, effects in the near-field with respect to the thermomechanical behavior of rock salt, the production of gases, etc. will be studied under conditions representative of a full-scale repository. Thirty boro-silicate glass blocks doped with Sr-90 and Cs-137 that have been manufactured at Battelle Pacific Northwest Laboratories (PNL) will be used. The test field has been completed and the technical components for transportation, handling, etc. are in an advanced stage of production. This demonstration is scheduled to start in 1990.

In January 1985, a political decision was made to develop spent fuel disposal without reprocessing to a technical solution in addition to the reprocessing option. An R&D program for DM 100 million was launched to cover all important additional repository-related aspects of this spent fuel management option. Several demonstration tests will be performed within this program, most of them in the Asse underground laboratory. In a Thermal Simulation Test of Drift Emplacement, electrically heated canisters with the dimensions and weight of the POLLUX cask type will be emplaced in drifts and backfilled with crushed salt. All relevant parameters such as temperature, pressure, room closure rate, compaction and porosity of the crushed salt, etc. will be measured and compared with computer predictions.

8.1.2.2. Underground Repository Konrad Iron Ore Mine

- Location: Salzgitter, State of Lower Saxony
- Planned for disposal of wastes with negligible thermal impact
- Licensing procedure in progress; license for construction and operation expected in 1991; start of operations planned for 1993.

The former Konrad iron ore mine is intended to serve only as a repository for nuclear waste with negligible heat generation. This contrasts with the Gorleben salt dome, to be discussed below, where the storage of heat producing waste is under investigation. Based on the results of the site investigations at Konrad that were performed by GSF and KfK between 1975 and 1982, PTB submitted an application for the proposed repository in August 1985. Due to the novel type of the licensing procedure and the special emphasis on long-term safety, the authorities raised further questions with regard to safety, going beyond the evidence submitted in the application documents for Konrad. As a result, the analysis process has been resumed and will add about one more year to the schedule. Start up of the Konrad repository is now expected for 1993 (Dickmann et al., 1988).

8.1.2.3. Underground Repository Gorleben Salt Dome

- Location: Gorleben, State of Lower Saxony.
- Planned for all kinds of solid waste.
- Surveyed from the surface mainly by drilling; results indicate promise of suitability; results from subsurface exploration by mining will be available in the late nineties.
- Start of disposal expected in 2008.

More details are given in the sections below.

8.1.2.4. Additional Activities in Federal Republic of Germany

- Participation in Grimsel project in Switzerland on disposal in granitic formations.
- Reconnaissance for potential granitic host rocks in FRG.

A Swiss-German cooperative agreement was signed in 1983 to enable the Federal Republic of Germany to participate in a broad testing program in the underground rock laboratory at Grimsel in Switzerland. This agreement was signed [illegible] the National Cooperative for the Storage of Radioactive Waste (NAGRA) for

Switzerland and the Research Center for Environmental Sciences (GSF) and the Federal Geological Survey (BGR) for Germany. The testing program is aimed at the development of geotechnical and geophysical investigative techniques as well as the determination of the suitability of granite as a geological barrier in underground radioactive waste repositories. The German research team is carrying out the following *in situ* tests:

(1) high-frequency electromagnetic measurements in boreholes,

(2) flow tests in fracture systems,

(3) stress measurements in boreholes,

(4) geophysical tiltmeter measurements,

(5) heating experiments, and

(6) macro-permeability tests in a ventilation room.

The first testing was started in 1983 before the excavation of the underground laboratory had been completed. Most of the other tests began in 1984-85 after extensive technical, geological and geophysical preparatory work had been performed by NAGRA and their contractors. Today, nearly all of this test program has produced results which are described in various reports (Brewitz and Pahl, 1986).

8.2. Gorleben

8.2.1. Status

In February 1977, the government in the State of Lower Saxony nominated the Gorleben salt dome as a candidate site for a waste repository. PTB, which at that time was the cognizant federal agency for construction and operation of repositories in the Federal Republic, in cooperation with the Federal Geological Survey (BGR) organized an extensive site investigation program to be carried out from the surface. This program was carried out between 1979 and 1983 (Jaritz et al., 1986) and had three main goals:

(1) hydrogeological investigations,

(2) geological investigations, and

(3) shaft pilot holes in preparation for underground exploration by mining methods.

The site investigation program from the surface will be completed by a final phase of an underground exploration program that has just started. This program consists of:

(1) salt petrographic investigations,

(2) geologic structural investigations, and

(3) geochemical investigations.

8.2.2. Geologic Investigations

From January 1980 through March 1981, four deep geological investigation boreholes, Gorleben 1002, 1003, 1004 and 1005, were drilled and cored on the flanks of the dome to a depth of about 2,000 m. They encountered all of the Zechstein strata with the exception of Zechstein 1. The evaluation of the results from these boreholes has been documented in several geological profiles published by BGR (Bornemann, 1987). All boreholes were plugged with clay and different special cements.

The Gorleben salt dome is situated in northwest Germany in the eastern part of Lower Saxony near the Elbe river, which here forms the border with the German Democratic Republic (DDR). The dome is about 15 km long and 4-5 km wide (Figure 8.1). During Late Permian (Zechstein) time, evaporites with a total thickness of about 1300 m were deposited in this part of Germany. This sequence of evaporites consists of six cycles (z1 - z6), the second and third of which contain potash layers; the first and last two cycles (z5 and z6) are very incomplete. In the Gorleben area, a diapir had formed by Keuper time that subsequently developed into a salt dome. During Late Jurassic and Early Cretaceous times, the dome broke through the enclosing sediments. From Late Cretaceous to Quaternary times, a caprock formed, above which Upper Cretaceous, Tertiary and Quaternary sediments were deposited.

The Gorleben salt dome, according to drilling completed thus far, consists of salt layers belonging to Zechstein cycles 2, 3 and 4. The succession of layers crossing the z2/z3 boundary consists of the following different units from bottom to top:

(1) The Stassfurt Salt consists of dark to light grey, medium and coarse grained rock salt. Fragments of coarse crystalline salt (grain size of a few centimeters) are common. Sulphate impurities are present in the form of nodules or flakes. In the lower and middle parts of this unit, these consist of anhydrite; in the upper part, polyhalite transcending upward into kieserite. Before the dome was formed, the Stassfurt Salt was 800 m thick.

(2) The Stassfurt Potash Seam is a carnallite layer about 20 m thick. The usually red or violet colored carnallite matrix encloses white fragments of kieserite several centimeters in size, as well as broken pieces of fine, pale grey rock salt.

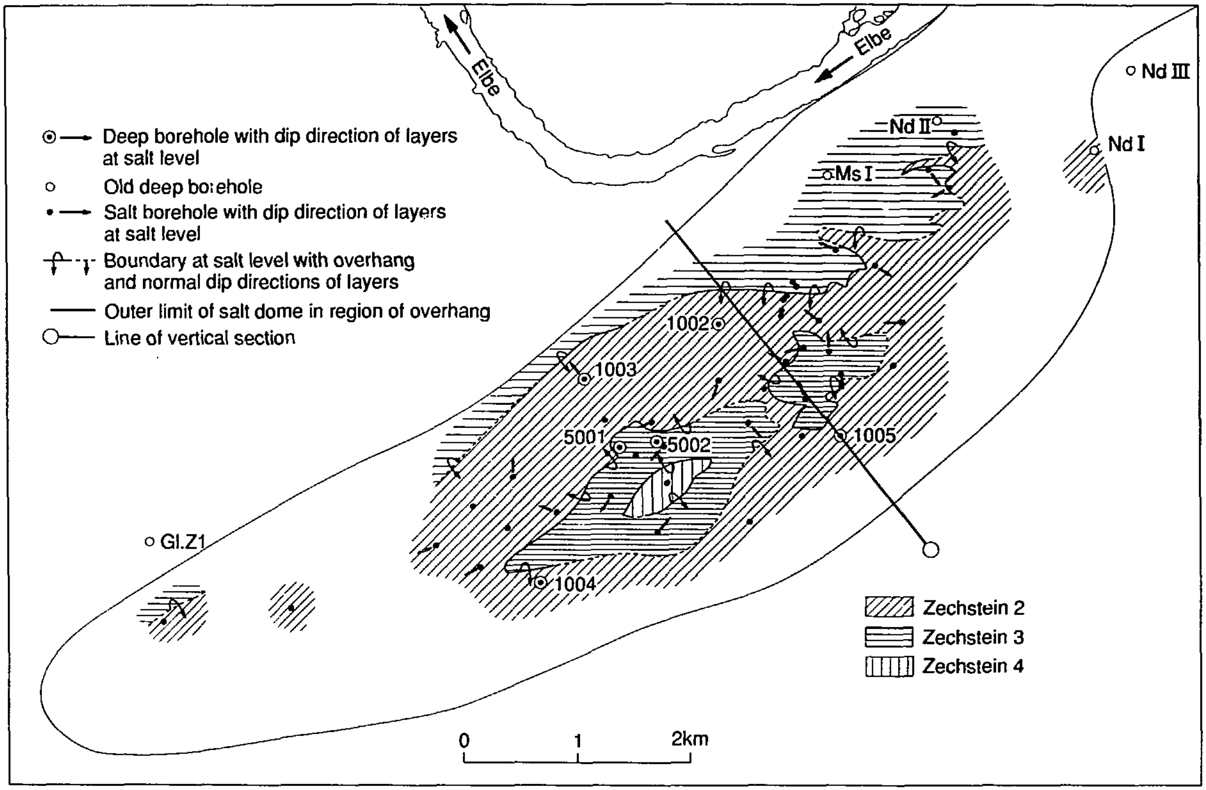

Figure 8.1. Gorleben salt dome. Location of boreholes and distribution of different types of rock salt at the top of the dome (geological map of the salt table).

(3) The Grey Salt Clay is the lowest unit of the Leine Series (z3) and consists of partly massive and partly thin-bedded, black claystone.

(4) The Leine Carbonate is a pale to beige grey, fine-grained, sometimes extremely fine-grained (homogeneous), magnesite rock containing some clay.

(5) The Zechstein 3 Anhydrite is anhydrite rock consisting of bluish-grey, fine-grained anhydrite in which veins, slickensides, and lamellae of magnesite occur.

During Quaternary time an erosion channel formed beneath the ice sheet covering the Gorleben salt dome. This channel belongs to a system of glacial channels that can be traced throughout northwest Germany. The channel above the dome originated during the Elsterian period of glaciation.

The thickness of the ice sheet covering the salt dome reached a maximum of 1,000 m during Elsterian time. The combined action of erosion by ice and meltwater and subrosion (subsurface dissolution of the salt) by meltwater led to the formation of a deep channel above the salt dome. This channel cut its way downward a maximum of 300 m through the the cover and caprock of the dome and into the salt itself.

Within the channel, the caprock was broken up by the erosive strength of the meltwater, and a breccia formed at the bottom of the channel above the salt (Bornemann and Fischbeck, 1986). The breccia consists of various types of rock debris from the cover and caprock. Thus, fragments of gypsum and anhydrite, several centimeters in size, are enclosed in a matrix consisting of clastic material from Upper Cretaceous, Tertiary and Quaternary sediments.

The structure of the salt dome is shown in the geological map of the top of the dome (Figure 8.1) and in the section across the dome (Figure 8.2). An examination of the drill cores shows that the fold axes suggest a gentle plunge parallel to the longitudinal axis of the dome. Thus, there is no evidence in the study area for steeply plunging curtain folds.

Two structural elements that extend over a large area can be observed on maps and cross sections. The first is the Stassfurt salt-complex in the main anticline of the dome. The anticline is bounded on the northeast by younger beds of z3 and z4. The second structural element is an inverted syncline of z3 and z4 beds southeast of the core zone. The southeast part of the syncline is bounded by a plunging fold of Stassfurt rock salt from the core zone. The width of the inverted syncline varies with the depth of its axis; the deeper the the axis, the narrower the structure.

8.2.3. Hydrogeological Program

From April 1979 until the end of 1984, 145 hydrogeology exploration holes, 326 monitoring wells and two coreholes were drilled over an area of about 300 km^2 as part of a hydrogeological program of investigations. In addition, 37 boreholes were drilled as much as 80 m into the salt itself to explore the surface of the dome. Pumping tests were also carried out.

This program has produced a detailed knowledge of the strata overlying the salt dome. These strata consist of a rather complicated system of Tertiary and Quaternary sands, silts and clays. A Quaternary channel, excavated by ice movement and crossing part of the dome, has been found. A protective clay layer, which may prevent subrosion of the salt, is weakened in this channel and is missing in places. The occurrence, salinity and flow of groundwater in the sediments overlying the salt dome are now sufficiently well known, and the results have been used in modelling investigations for a preliminary safety assessment evaluation.

A groundwater flow rate of several m/yr has been computed for a depth of 170 m below mean sea level (Figure 8.3). The flow field mirrors the hydrogeological setting of the salt dome. Outside the structure of the dome, the groundwater flows in the surrounding Miocene sands. Above the dome, high velocities have been computed for the Quarternary subglacial channel system where the main channel crosses the dome from south to northeast. At greater depths, the model results indicate that flows of more than 1 m/yr occur only in the main channel and in the Tertiary sands northwest of the dome (Jaritz et al., 1986).

8.2.4. Planned Underground Exploration

The starting point for the underground exploration program is to identify the problems to be investigated. At the same time, one must determine how the data will be used to solve these problems and how important the problems are in order to set priorities and decide which methods should be used. It is also necessary to determine which answers will provide new information. Uncertainties in the data must be quantified as far as possible because any effort to improve data precision can be justified only when this is done. The detail to which the underground exploration is to carried out is governed in the end by the degree of certainty required of the

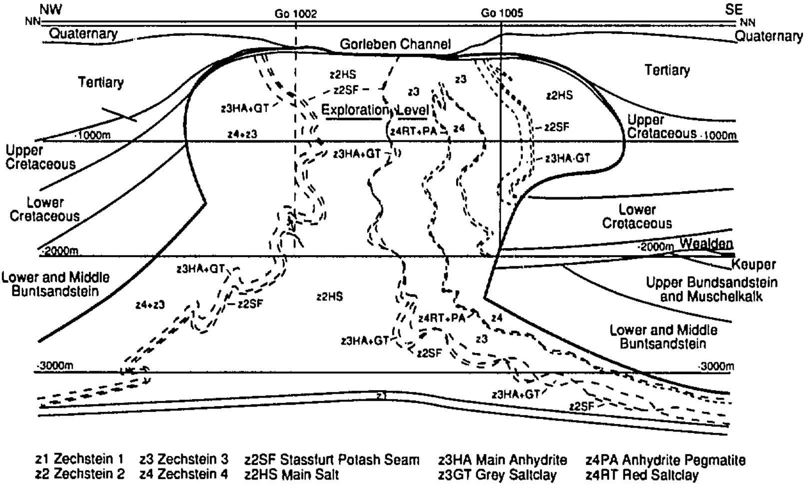

Figure 8.2. Cross-section of Gorleben salt dome - structure geological features.

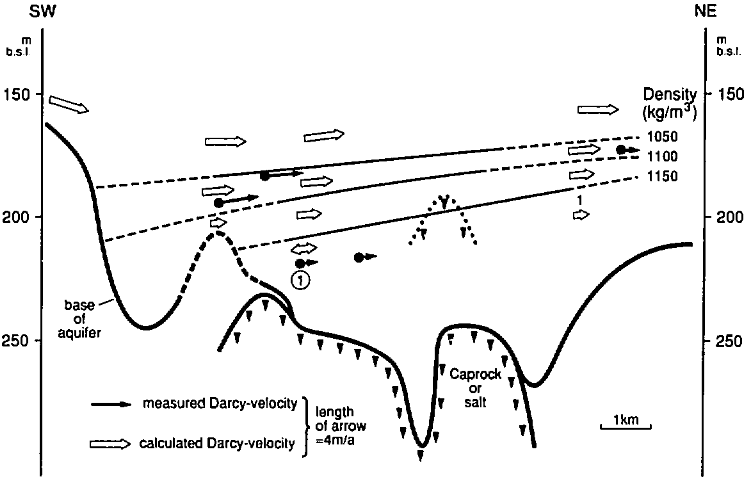

Figure 8.3. Section through aquifer on top of salt dome, showing density and velocity of saline groundwater.

data. This can vary depending on the problem to be solved.

The identification of problems and their priorities requires a systematic examination of the measures necessary for planning, construction and operation of the repository (Langer and Venzlaff, 1988). This examination shows that the underground investigations have three essential tasks as shown in Figure 8.4:

(1) assessment of the thermomechanical load capacity of the rock salt so that emplacement strategies can be determined for the site,

(2) determination of the safe dimensions of underground openings (e.g. cavern stability and mine safety), and

(3) evaluation of geologic barriers and long-term safety analysis to satisfy authorization procedures (Langer, 1988).

Geotechnical and geological data are needed to answer the various questions associated with these three tasks. The following are examples of some of these questions:

(1) Are the homogeneous parts of the rock salt large enough for the repository?

(2) Which failure scenarios cannot be excluded on the basis of the structure of the salt dome?

(3) Can the required width for the safety zones between the repository and unfavorable layers (e.g. main anhydrite and carnallite) be observed?

(4) What is the load capacity of the rock under the expected thermomechanical stress changes (e.g. rock burst and creep rupture)?

(5) Will the caverns become unusable as a result of convergence, dilatancy or subsidence?

(6) Can the thermal load induce decomposition of the minerals (e.g. loss of water of hydration) or a hazardous migration of brines?

(7) Can an uncontrolled generation of gases or brines be avoided?

(8) Will the integrity of the salt dome be jeopardized by long-term changes in stress (e.g. fracture formation)?

An extensive and detailed characterization of the salt dome that is based partly on underground exploration must be performed to answer these and other similar questions (Figure 8.5). This characterization combined with the requirements given in the repository concept, the design of underground drifts, and the failure analysis will be used as a basis for deciding the suitability of the salt dome as a host formation for a permanent repository for radioactive waste. This process will be documented for the authorization procedures.

8.2.5. Calculation of Integrity of Salt Dome Barrier

The question of how well the salt formation can sustain thermal loading was raised early for the Gorleben site and has been the subject of many investigations in the FRG. Thermally induced deformations and the related stress fields as well as their influence on barrier integrity have been studied from the geomechanical point of view.

Heat generation resulting from radioactive decay decreases with time. Therefore, temperatures initially are increased in the vicinity of the repository causing thermal expansion. This, however, results in thermally induced stresses because the rock builds up a transient resistance to deformation. As temperatures decrease at later times, the rock mass tends to contract and stresses are reduced in the repository area (Figure 8.6).

An assessment of the integrity of the geological barrier can only be based on calculations. Preliminary design calculations have been oriented toward problem identification and an indication of possible trends. At the present stages of exploration at the Gorleben salt dome, the final input data for the computational model are not yet sufficiently available.

Temperature distributions with time and the related far field stresses have been computed for specific disposal conditions. A maximum temperature of 455 K after 150 years was obtained, and the maximum uplift at the surface after 2,000 years amounts to 3.3 m. Under certain conditions tensile stresses may develop in the caprock (Wallner, 1986). All numerical calculations are performed using the ANSTALT code (Wallner and Wulf, 1983).

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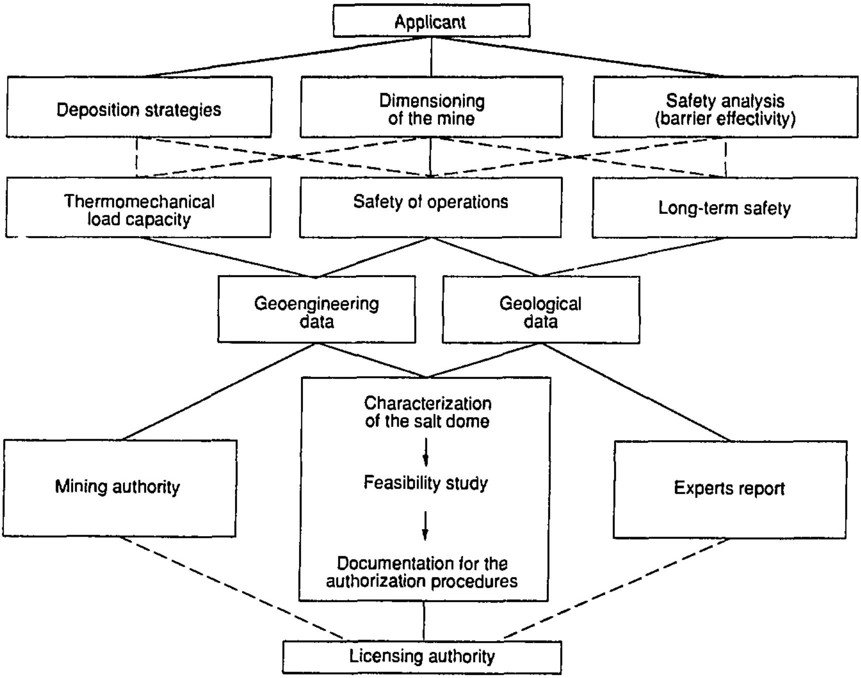

Figure 8.4. Information and data flow for the underground exploration.

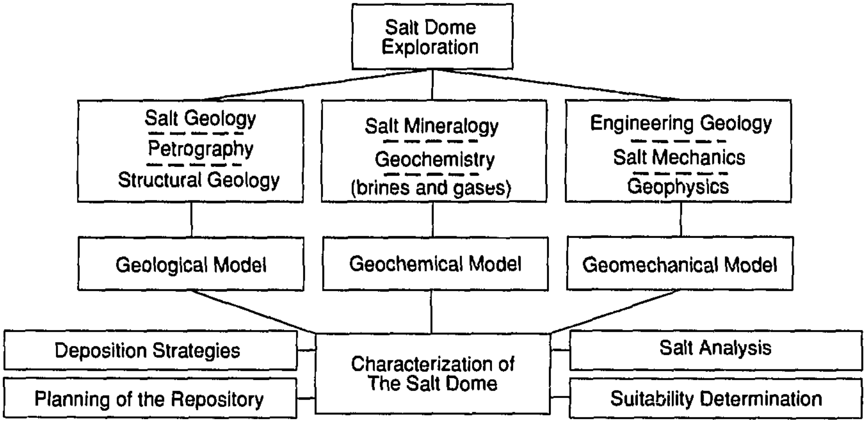

Figure 8.5. Objectives of the salt dome exploration.

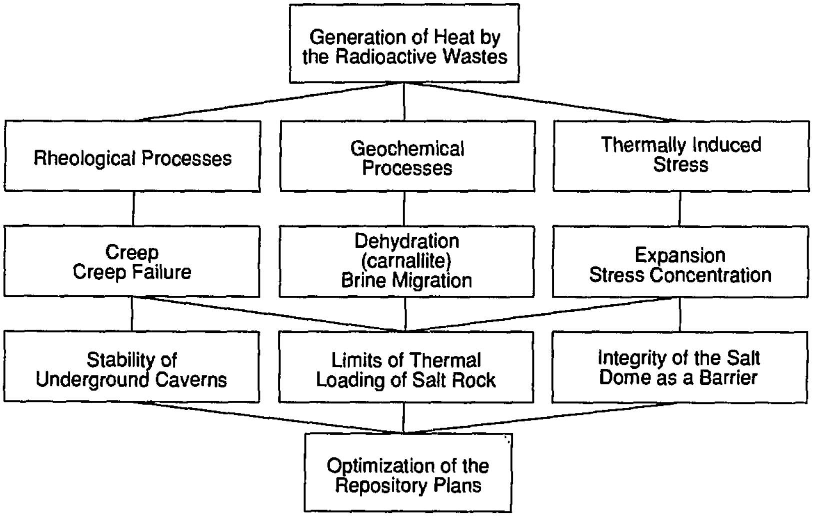

Figure 8.6. Thermomechanical response due to generation of heat by the radioactive wastes.

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Chapter 9

Geological Aspects on the Assessment of an Underground Depository for Low- and Intermediate Level Radioactive Wastes in a Former Salt Mine (G.D.R.)

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9.1. Basis

Since 1978, low- and intermediate-level radioactive wastes from nuclear reactors and the production and application of radionuclides have been emplaced in a former mine (potash and rock-salt exploitation). The final repository is located in an extended salt-diapir (Zechstein/Upper Permian) within the present humid-temperate climate zone of Middle Europe. As a result of the classic potash exploitation that has continued from the end of the last century, extensive geological and hydrological data are available.

9.2. Task and Method of Investigations

The main objective of the complex geological-hydrological investigations during the 60's and 80's was to prove the long-term stability (10^4 - 10^5 y) of the diapir. The geological-structural, hydrogeological, hydrochemical and geophysical investigations are complemented by geodetical (recent crustal movements) and seismological data.

9.3. Regional Geological Situation

The diapir is situated at the southern margin of the Northgerman-Polish Basin (transitional zone between regional salt-pillow and diapir tectonics) and is structurally controlled by NW-SE fracture deformation of the Permo-Mesozoic Complex. As a result, Triassic and Jurassic pelites and the psammites of the transgressive Maastrichtian are collapsed in grabens (Allertal zone of the northern Subhercynian Basin). Palaeocene and Quaternary are undeformed. The whole region is now non-seismic.

9.4. Structural Development

The diapir development began 230 my ago as a "fracture diapir" (Triassic, Early Kimmerian tectonics), the main development followed during the Late Jurassic (130 - 135 my, Late Kimmerian). Laramic tectonics are characterized by decreasing subsequent movements as a result of the complete separation of the salt from the attending marginal structures of the diapir (balance of the palaeotectonic strain condition).

9.5. Hydrogeological Regime and Suberosion

The main groundwater reservoir above the salt-diapir consists of porous and jointed rocks, through which the movement of the surface water and superficial groundwater (freshwater) is directed to the graben structures of the diapir. The deepwater (NaCl type, <350 g/l total mineralization) is mineralized to a high degree and slightly strained. The replaced freshwater and mineralized groundwater is now stagnating. As a result of a regional suberosion, a salt washed surface was generated approximately 250 m underground that is now overlain by a thick caprock (gypsum, anhydrites), isolating the salt of the diapir. The amount of suberosion during the last 100,000 years is probably 0.05 mm/a. The age of the water in the caprock is approximately 100,000 years.

9.6. General Development of the Diapir

The complex analysis of the development of the diapir and its interaction with the hydrogeological regime demonstrates a stage-like decreasing tendency of vertical salt-movement and as a result, suberosion in the top of the diapir.

9.7. Technical Utilization of the Repositories

The low- and intermediate-level radioactive wastes are mainly emplaced in former rocksalt mines. The influence of heat and radiation on the rocksalt has been investigated by in situ experiments (Ebel and Richter, 1986).

The results achieved from geological investigations of underground repositories in diapir-structures are suited for methodology comparisons in analogous areas of the world.

9.8. References

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Editors note.

The recent changes leading to the unification of one Germany produced a situation such that the authors were not able to submit their planned report in time for inclusion in this review.

Chapter 10

Repository Site Selection and Characterisation Programme for High Level Waste Disposal in India

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10.1. Introduction

India entered the era of commercial nuclear power exploitation in 1969 with the commissioning of Tarapur Atomic Power Station of 420 MWe capacity. Thereafter, the nuclear power generation gradually increased to the present level of about 1600 MWe, which is planned to be increased to 10,000 MWe by the year 2000. The spent fuel from power reactors is reprocessed to recover plutonium and uranium for reuse as fuel in suitable reactor systems.

High level radioactive waste (HLW) from reprocessing is solidified and will be finally disposed of in an engineered repository located in deep geological formations. Disposal in a geological formation is considered to be safe, since it has the potential to provide isolation of radioactive waste from the biosphere over extended periods of time. Further, the favourable characteristics such as massiveness, compactness, homogeneity, vastness and capability to withstand physico-chemical, hydrological, mechanical and radiological effects, are ideally suited to the safe disposal of waste.

Important steps involved in the management of HLW in the Indian nuclear programme are: (1) vitrification, (2) interim storage for 20-30 years of the vitrified waste in an engineered, near surface storage facility with cooling and surveillance and (3) ultimate disposal of vitrified waste in a deep geological repository.

Technology for the first two steps has already been fully developed and plants have been built in India. In so far as the third step is concerned, a plan of action has been worked out. It envisages establishment of a deep repository at a suitable location. Many massive and extensive host rock formations of granite, basalt, clay, shale and granite gneiss are available in different parts of the country. Out of these formations, granite and granite gneiss are considered to be more suitable for locating a waste repository site. With this in view, various regions in India were considered and some of the regions with granitic rock formations have been taken up for detailed investigations.

As a part of repository host rock studies, an underground experimental facility has been set up to study thermomechanical behaviour of rock formations consequent to heating. Based upon the results of the above investigations, a pilot repository will be established, for studies with actual vitrified waste canisters.

10.2. Geological, Tectonic and Hyorological Features of India

India is a vast country and has varied geological, tectonic and hydrological features and every region is unique in this respect. Figure 10.1 shows some of the important geological features of different regions of the country. It can be seen that in the north there are massive Himalayan ranges which comprise thick sediments from pre-Palaeozoic to Tertiary age. These structures are however tectonically unstable being in an orogenic belt (Figure 10.2). The Himalayas are followed southward by the vast Thar desert and Indo-Gangetic planes which fall in high seismic zones. From the central part of India up to the western coast there are extensive flows of basaltic lava, known as the Deccan trap. Some portions of the Deccan trap are thick and massive in nature and may find favour for consideration as repository host rock.

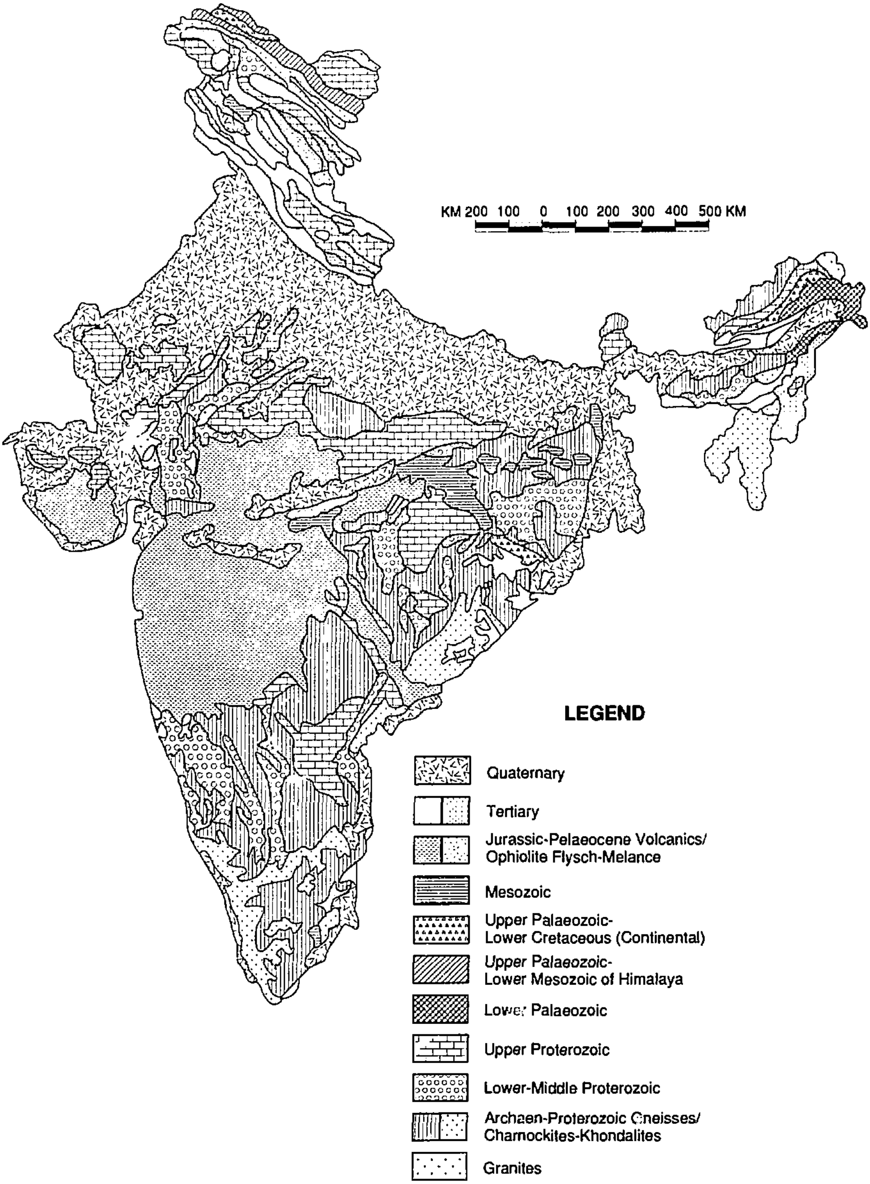


Figure 10.1. Geological map of India.

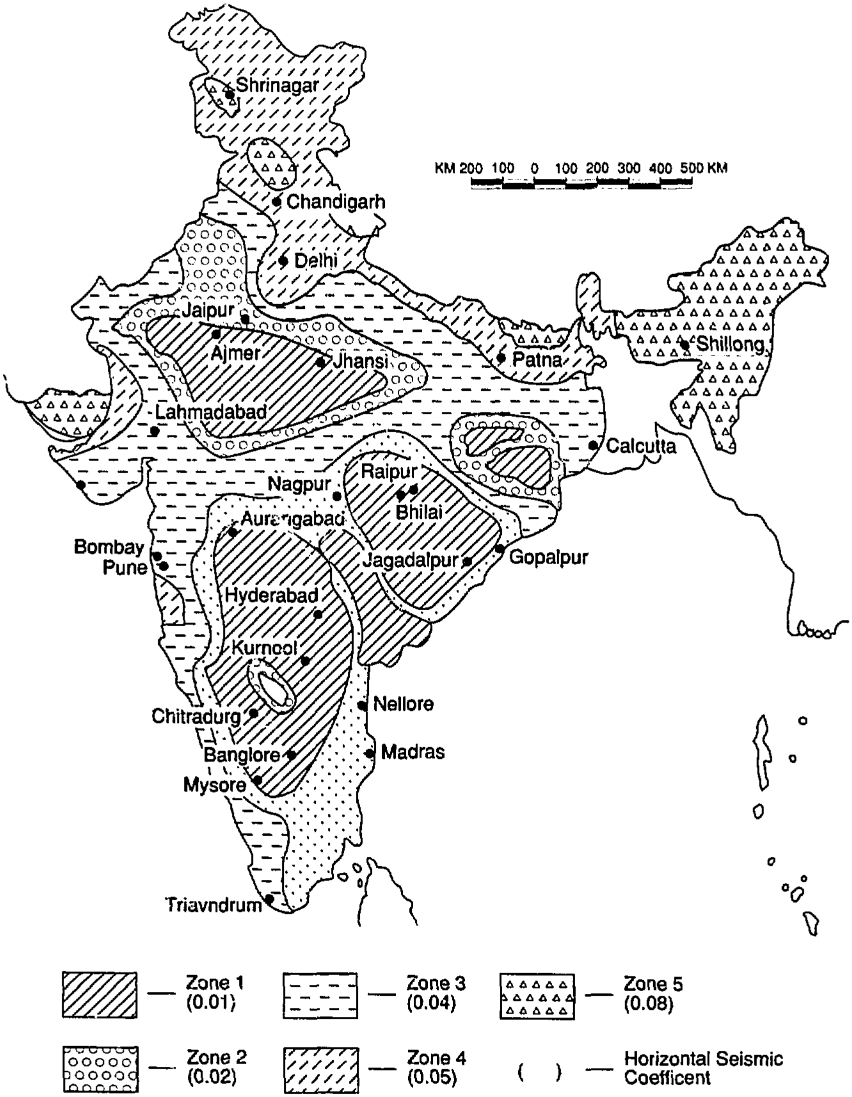


Figure 10.2. Seismic zones of India.

The southern peninsula consists of homogeneous and monolithic crystalline formations of granite and granite gneisses. This region is tectonically stable and hydrologically favourable as shown in Figures 10.3 and 10.4. These features invite further detailed investigations to establish the suitability of the host rock and identification of repository sites.

10.3. Characteristics of Major Host Rock Formations

Granite and granite gneisses which are under consideration have very favourable thermal, mechanical, radiological and sorption properties required for repository host rock. Plutonic granite formations viz: Closepet granite, Patna granite etc., of the southern peninsula are coarse grained porphyritic, grey to pink coloured granites, massive in character. There are distinct sets of joints. The granites are traversed at places by basic dykes. Ground water occurs only at shallow depths.

Granite gneisses of the peninsula are wide spread and are available over a major part of the southern shield. They include granite gneisses, composite gneisses, granodiorites etc. The gneisses are of three types; (1) uniformly medium to fine grained, light grey gneiss or gneissose granite, (2) coarse foliated dark coloured gneiss with porphyritic crystals of white feldpars, and (3) highly crumpled and foliated dark grey biotite gneisses. Some locations in areas consisting of Patna granite, Closepet granite and peninsula gneisses are being considered as repository candidate sites. Similarly, Bundelkhand granite and granite occurrences in Rajasthan are also being evaluated for location of candidate sites.

In addition to the granitic formations discussed above, basalts of the Deccan trap are also being investigated for their suitability as repository host rocks.

10.4. Site Selection Criteria

In order to have a judicious choice of the waste repository site, it is necessary to study carefully the different factors and to formulate basic criteria for the purpose of site selection. The basic factors that are considered for developing the site selection criteria are: (1) tectonic stability, (2) rock characteristics, (3) hydrological and environmental factors and (4) socio-economic factors.

10.4.1. Tectonic Stability

Tectonic stability of an area is the most important factor as the integrity of the repository and waste containment system would mainly depend on the stresses, vibrations and movement of the host rock. In this regard only areas with 0.02 or less *horizontal seismic coefficient are* considered to be safe. Major structural features, such as faults, thrusts, lineaments, folds, shear zones etc. should preferably be absent at least within a radius of 100 kms. Volcanic activity within 500 kms is also not desirable.

10.4.2. Rock Characteristics

The host rock should essentially be homogenous, massive and compact in three dimensional geometry. Topography and the weathering pattern of the rock have a direct bearing on the erosional effect by water, wind and chemical decomposition. They also indicate rain water recharge and aquifer potentiality. As such, thick soil cover and weathered zones are not considered favourable. A thin clayey soil cover at the repository site helps in preventing infiltration of rain water in the ground and also retains radioactivity at the surface. The host rock should have gentle dips of the formation as well as foliations, so that the aquifer is confined to shallow horizons, thus preventing the movement of radioactivity to and from repository depths. Highly jointed and fractured formations are not favoured, since such formations act as host media for ground water aquifers and provide pathways for movement of radionuclides. Figure 10.5 shows some of the important geostructural and hydrological features of the different host rock formations mentioned above.

The other important factors in the selection of a host rock are the thermomechanical properties and their interactions with radioactive materials. Integrity of the containment system of the repository is highly dependent on these factors.

10.4.3. Hydrological and Environmental Factors

Ground water is the principal agent for radionuclide migration and transport to the biospbere. Therefore, complete knowledge of the hydrological system of the repository site is essential. In view of this, data with respect to rainfall, run-off, recharge, flooding etc. over an extended period of time should be available.

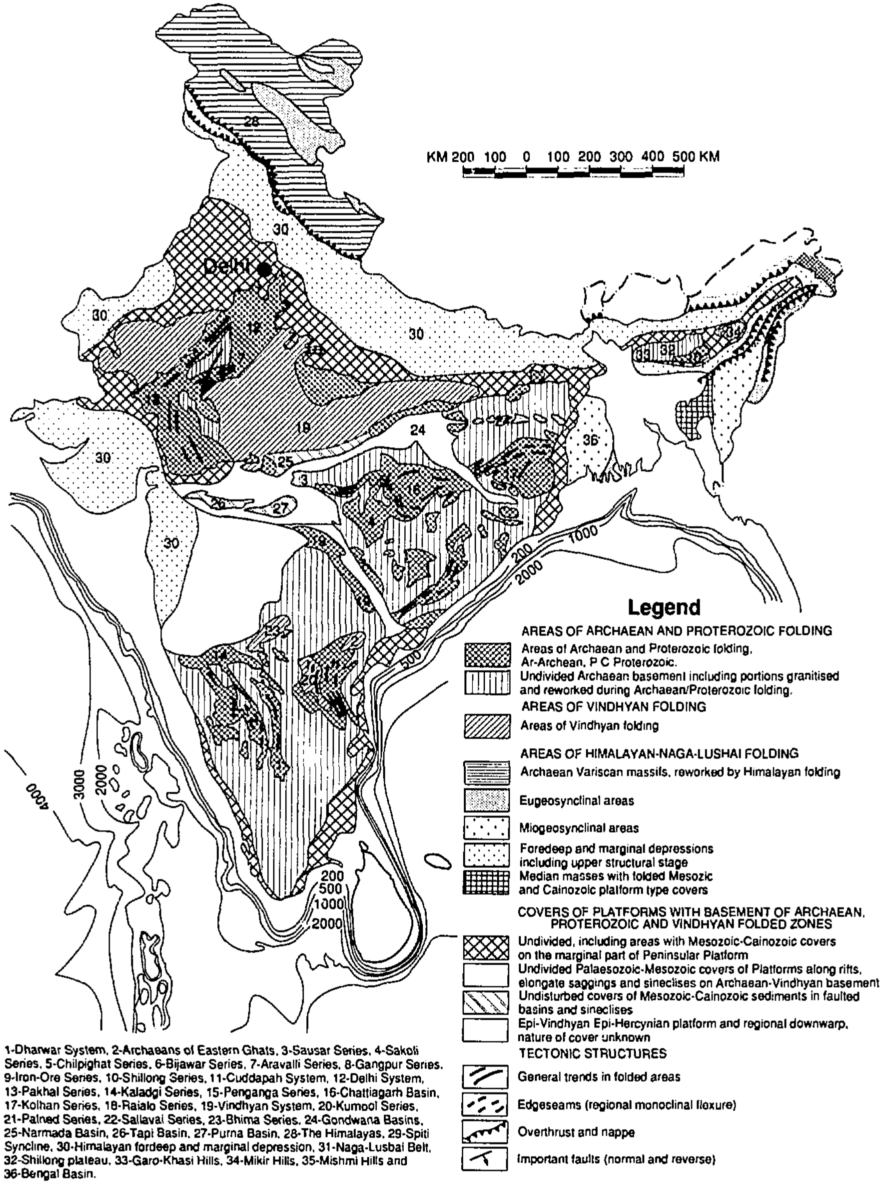


Figure 10.3. Schematic tectonic map of India.

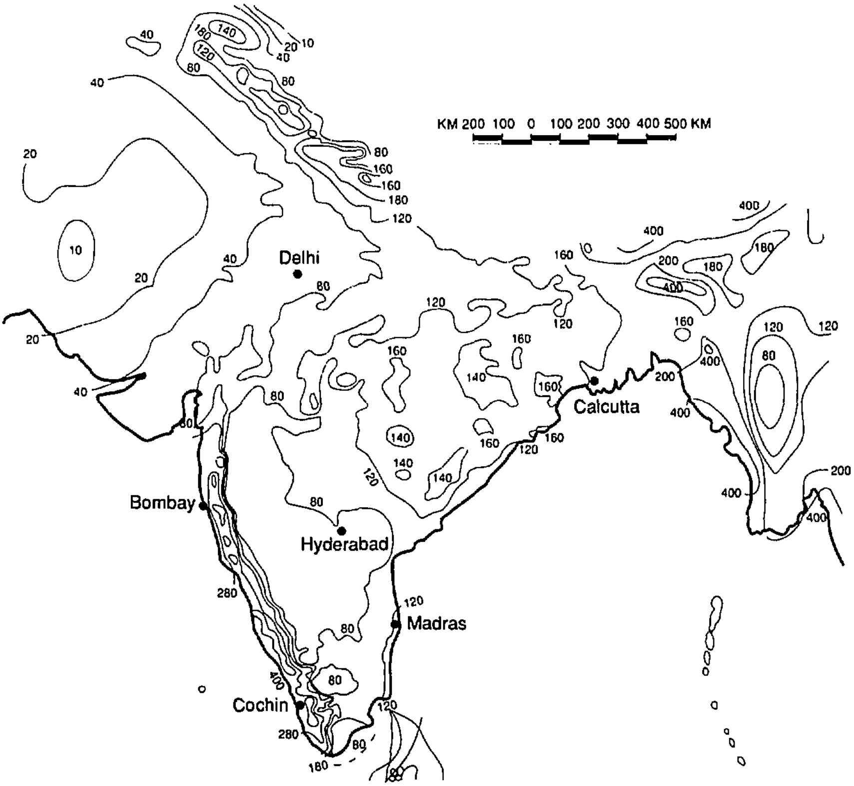


Figure 10.4. Rainfall map of India.

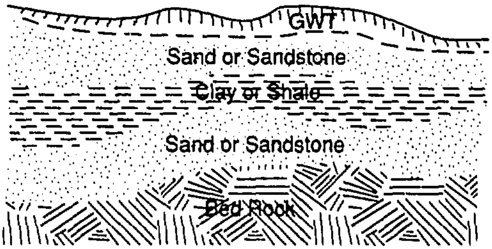
Areas covered with ponds, lakes, rivers, dams etc. are avoided for the repository site. Locations with no ground water are most favourable. However, under certain situations thin aquifer zones with low ground water flow may also be considered.

10.4.4. Socio-Economic Factors

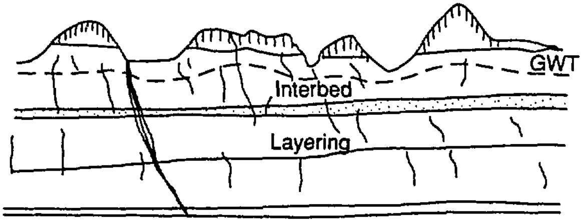
The socio-economic and political situation of the region has a bearing on deciding upon the location and siting of a waste repository. In this context, for the ready acceptibility of such a repository by society, it is desirable that the site be located in remote areas with a low population density and easy accessibility. It should also be ensured that the areas considered are kept out of the purview of mineral exploitation and idustrialisation for any foreseeable future.

10.5. Site Investigation and Characterisation Programme

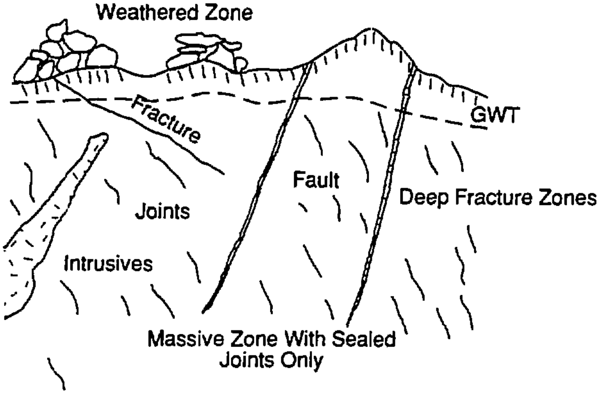
A detailed programme with respect to site investigation and rock characterisation has been formulated keeping in view the criteria discussed above. The programme has certain important features which will be implemented through the following stages:



CLAY AND SHALE



BASALT



GRANITE AND GNEISSES

Figure 10.5. Sketch showing surface, subsurface and structural hydrological features of the rocks having significance for selection of a repository site.

10.5.1. Stage I

This phase of the programme consists mainly of screening the country as a whole on a broad basis to narrow down the choice of the areas for consideration and evaluation. The major part of the work in this regard has already been completed and suitable regions in the central and southern part of India have been identified.

10.5.2. Stage II

The next step involves collection and interpretation of data related to geohydrological, tectonic and socio-economic conditions of the regions as identified in Stage I. Such data has already been collected to a large extent and based on this data, some areas have been earmarked for detailed investigations. These areas lie in granitic and gneissic formations of the southern peninsula shield.

10.5.3. Stage III

A detailed programme for field surveys, mapping and study of local data has been drawn up and semi-detailed investigations to restrict the area as a candidate site, with an area of about 100-150 sq. kms., have already been selected for further subsurface and micro-investigations.

10.5.4. Stage IV

At this stage it is planned to go for micro-studies relating to subsurface characterisation of the rock formation. This will involve extensive geological and geophysical field surveys and mapping which will help in further reducing the area of investigation to 30-50 sq. kms. Once this objective is achieved, deep boreholes and geological and geophysical logging will be carried out to get an insight of the strata under review. Subsurface investigations also include groundwater quality and movement studies. Rock core samples obtained from the borehole drilling will be subjected to a number of tests to obtain the necessary information on rock characteristics.

10.5.5. Stage V

Based on the information received through the above stages, sites for the pilot repository will be decided and a pilot repository will be set up at one of these selected sites for in-situ experiments and testing purposes. A conceptual layout of such a pilot repository has been prepared and is shown in Figure 10.6. These studies involve investigations with respect to the following important parameters:

(1) Effect of blasting
(2) Rock stress measurements
(3) Mechanics of deformation
(4) Pillar stability
(5) Near field response of rock mass and time-temperature relationships
(6) Thermal conductivity and diffusivity
(7) Thermal expansion
(8) Waste-rock-groundwater interactions
(9) Solubility of waste form and its container at elevated temperature
(10) Sorptive properties of media in the flow path
(11) Study of joints and fractures
(12) Testing of mining, transport and remote handling equipment.

10.5.6. Stage VI

This is the final stage and involves planning and setting up of a full-fledged high level waste repository.

10.6. In-Situ Thermomechanical Investigations

Since the work of setting up a pilot repository will require some more time, it is felt desirable to collect some of the important data on the rock formations under consideration. In this connection, an experimental facility has been set up to study the in-situ thermomechanical and sorptive properties of similar rock in an existing underground mine facility. The facility is located at a depth of 1000 m in a chamber and consists of electrical heaters for simulation of the vitrified high level waste canisters. The objective of the experiment is to find out the behaviour of the rock mass consequent to heating. In one of the experiments, a single heater is used as the main central heater and eight peripheral heaters are employed for accelerated heating in a circular pattern on the floor of the chamber as shown in Figure 10.7. The heaters are embedded in the rock mass with the necessary temperature, stress and extension measuring devices. This experiment has been in progress for quite some time now and data on temperature distribution, thermal conductivity, heat induced stresses and expansion in the rock mass at increasing heat flux of the electrical heaters have been collected and are being analysed. The data obtained from the experimental facility is found to compare well with the predictions made using the computer model, developed earlier.

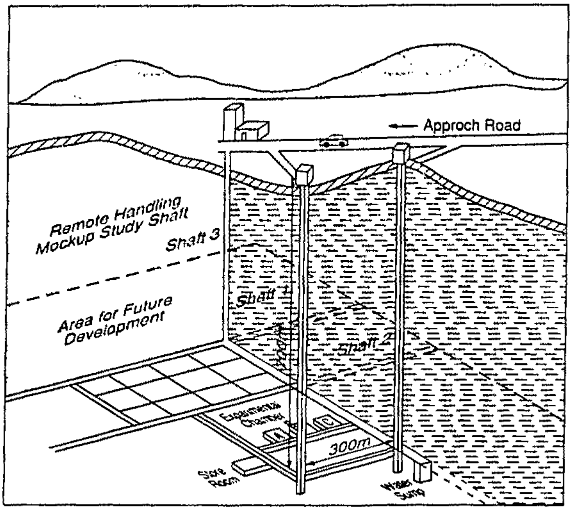


Figure 10.6. Conceptual layout of pilot repository in granite.

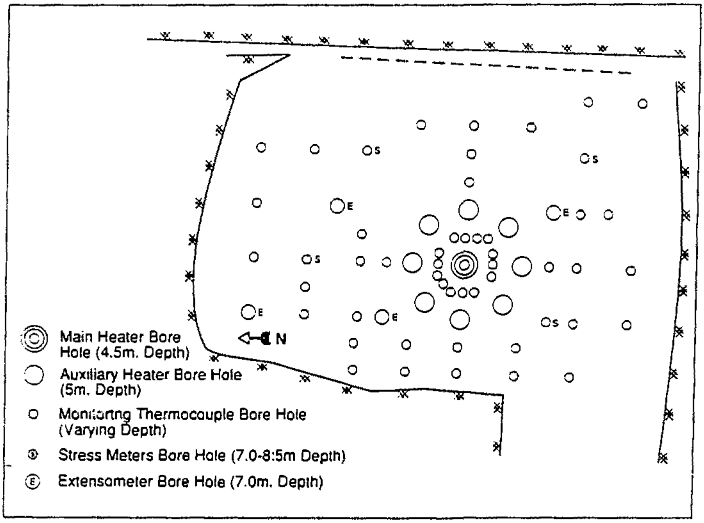


Figure 10.7. Heater array for in-situ thermomechanical experiment.

In another set of experiments, five electrical heaters are installed in a triangular and rectangular pattern. The objective of this experiment is to evaluate the pitch and orientation of disposal boreholes and the total heat load that is likely to be placed on the host rock.

10.7. Conclusion

The future of nuclear power generation is very much dependent upon successful management of high level radioactive waste in a safe manner. Keeping this in view, India is pursuing a well planned programme to attain the capability of setting up deep repositories for disposal of vitrified high level waste.

Chapter 11

Natural Analogues and Evidences of Long Term Isolation Capacity of Clays Occurring in the Italian Territory

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11.1. Summary

This work concerns the results of studies conducted at many sites in Italy aimed at collecting information on the natural evidence of the isolation capacity of clay. Most of the work done has been carried out with the coordination and financial participation of the Commission of European Communities (CEC). No sites reported here have been studied for waste disposal purposes.

Field observations provide the opportunity to know directly, or to infer, the evolutionary geologic processes that are of concern for waste disposal problems. Such observations have the major advantage that they involve natural phenomena acting over the same, or even greater, time-space scale that is involved in the geologic disposal of wastes. The field situations explored have been focussed on the secondary permeability of clay that was determined by means of natural tracers (Hg, He, hydrothermal and geothermal fluids, etc.) either at the surface or in deep civilian tunnels.

Another topic treated here is the oxidation-reduction front as a control factor in the physicochemical environment of clay as well as radionuclide migration. The mechanical and thermal effects that result from the intrusion of a subvolcanic body into clay represent an extreme worst case by comparison with the effects on clay caused by the heat developed by radionuclide decay. Finally, the isolation of a fossil forest that has been maintained almost unaltered for over one and a half million years is described. All these results from geologic observations point unequivocally to the long lasting capacity of clay formations to provide an environment of almost total isolation.

11.2. Introduction

Some of the recent clay formations of Italy are spectacularly exposed on hills and valley slopes. Traces of the genetic as well as early and late evolutionary phenomena can easily be "read" in the field in the geological records. This represents a real advantage by comparison with the small scale observations and the experience that currently is obtained with samples, boreholes and short tunnels. Indeed, field observations can be made directly at the same time-space scale that is of such concern for the disposal of long-lived radionuclides. Moreover, these observations are not superfluous in the context of the problems of isolating low level, short-lived radioactive waste.

Clay formations may play at least two roles with regard to the different options being considered for waste disposal:

- direct containment where the clay is used as the host rock, and
- isolation of a different type of host rock for the waste deposit.

Generally speaking, geological formations used for waste isolation must assure long term hydrologic isolation. From this point of view, the potential development of a secondary permeability due to the effects of tectonics and its various consequences must be taken into consideration in site selection. The ion-exchange capacity of the host rock as well as its physicochemical effects on radionuclide behavior constitute another important aspect. With relation to the latter factor, the oxidation-reduction front in a clay formation corresponds to the potential plane separating the mobile from the stable phases of the transuranic elements. This front is easily seen in the field.

Modifications induced by the heat generated by high level radioactive waste may cause an alteration of the selected host rock and its properties. The importance of this alteration compared to the required duration of waste containment is often overestimated. Indeed, a modification of the rock that is modest by comparison with conditions in the total volume of host rock does not significantly affect the geologic barrier. This is clearly demonstrated in the case of the effects of natural heating of clays in Italy.

Most Italian clay deposits are cut by deep civilian tunnels. Much information on seepage and major water inflows into tunnels can be obtained from the engineers on such projects.

The distribution of fluids emanating from geothermal fields and the noble gases from the mantle, such as helium, are very effective indicators of the impermeability of clay formations. Helium represents a potentially powerful tool in the exploration for the most appropriate disposal sites.

The long term preservation of tree trunks within clay is striking evidence of the isolation capacity of clay with regard to oxygen from the atmosphere or from phreatic water. The ion exchange capacity of clays is not considered here because the data are mainly derived from laboratory analyses. However, it must be kept in mind that variations in the oxidation-reduction potential as well as in other controlling factors may qualitatively modify but not eliminate the ion exchange capacity of clay.

11.3. Clay Impermeability as Revealed by Natural Tracers

Undisturbed clays are currently presumed to be almost impermeable. In risk analysis, the migration of water along faults and fracture planes is assumed to be one of the most important pathways for radionuclides to migrate from the repository to the biosphere. As a matter of fact, the permeability of clays in relation to tectonic structures is generally inferred from theoretical considerations that are based on local and laboratory observations. This evidently limits the reliability of the conclusions that can be drawn relative to the actual overall hydrological behavior of clay formations. Large scale field observations may contribute definite evidence to overcome this problem.

Hydrothermal waters and gases, as well as fluids and gases from geothermal reservoirs, rise from great depths along fault planes. This fact and other natural tracers, such as mercury and the very sensitive helium, may be considered as useful indirect indications of the impermeability of argillaceous formations. This is well demonstrated in central west Italy where ancient and present hydrothermal activity, geothermal fields and mercury deposits are frequently contained in the basement underlying the clay deposits. Field investigations designed to locate fluid pathways related to tectonic structures have been conducted in southern Tuscany and northern Latium (Polizzano et al., 1986) where the present Orcia and Paglia valleys correspond to deep Pliocene trench basins of the the horst-graben type (Calamai et al., 1970; Squarci, 1981). This is shown schematically in Figure 11.1.

As shown on Figure 11.1, fault planes intersect the basement of the Orcia-Paglia basin, which is composed of mixed chaotic clays and marls emerging in the form of horst pillars. The floor of the basin is more than a 1,000 m deep, and the basin is filled with beds that are predominantly clay. An important geothermal source underlies the basin (Brondi and Polizzano, 1986), and an important level of thermal activity exists throughout the basin.

Hydrothermal fluids may be coming from two separate sources: a system of deep regional faults and the geothermal reservoir. The first source is mainly responsible for important emissions of both carbon dioxide and hot water (20-52°C), from which very large deposits of travertine are generated. The geothermal field (Marinelli, 1963) produces an upwelling of very hot fluids (150-250°C, 40-60 atm) and the thermal mobilization of mercury in the deep substrata. Mercury is precipitated in the form of cinnabar (mercury sulphide) in the surrounding lower temperature rocks or directly at the surface (Figure 11.1).

The presence of helium in soil provides a powerful means of revealing permeable underground structures (Lombardi and Polizzano, 1988). Helium originates in the mantle and tends to rise to the surface by migrating along discontinuities, such as important fault zones. Helium, of course, has the smallest atomic radius of all the elements. Being chemically inert, it doesn't react with the host rock and is not subject to capture as a result of the exchange capacity of minerals. In an absolute sense, helium is the most mobile element within the earth.

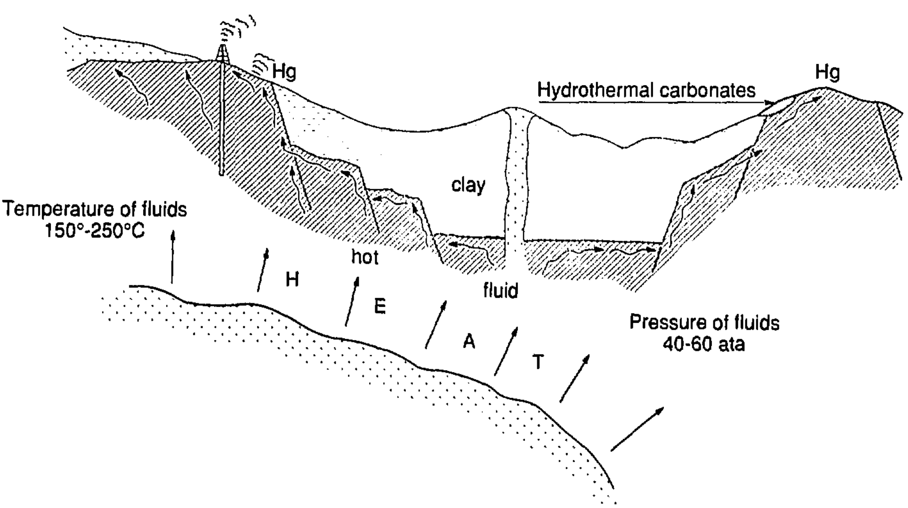

Figure 11.1. Clay as an impermeable obstacle to geothermal fluids rising to the surface. (Paglia-Orcia Valleys)

Data were collected on the locations of both hydrothermal and geothermal products within the Orcia-Paglia basin. The main results are as follows:

(1) the locations of gas and hot water emissions correspond to the boundaries between clay deposits and the horst pillars,

(2) important deposits of travertine accumulate in the same locations,

(3) vapor from the geothermal fluids is all confined within the chaotic clay-marl complex of the western horst pillar and does not permeate into the Pliocene clay series,

(4) important concentrations of cinnabar and other rare minerals occur in the two horst pillars, and

(5) helium crosses the clay series in the central part of the basin only along active faults, and its migration is strongly controlled by age of the fault movement.

Where the clay is unaffected by tectonics, it appears to be much less permeable or totally impermeable to helium. Of course, pathways for the migration of such an easily mobile element may be completely impermeable to other natural tracers as well as radionuclides.

The above results provide strong evidence for the almost impermeable property of clay deposits, a property that can prevent very energetic endogenous fluids from reaching the surface. These fluids can reach the surface only by migrating up deep fault planes on the borders of the basin where the clay layers tend to become thinner and are interbedded with sandy layers that affect the homogeneity of the clays.

11.4. Secondary Permeability Due to Tectonics

Direct observations on permeability caused by fracturing and faulting in clays have been made in Italy (Brondi and Polizzano, 1986; Chiantore and Gera, 1986) both at the surface and underground in tunnels constructed for engineering purposes. Practically all argillaceous formations in Italy, regardless of age, are overconsolidated (Chiantore and Gera, 1986); only very recent Quaternary clays are normally consolidated. It appears from field observations that the response to fracturing and the permeability that is induced in clay masses vary widely due to an interplay between many factors. Fracturing is a common feature in the normal or chaotic argillaceous formations of Italy. Up to the present, no evidence of intact undisturbed clayey materials has been found.

11.4.1. Observations in Tunnels

From observations in tunnels, it has been possible to investigate other clay series including ancient chaotic clays in addition to those of the Plio-Pleistocene. A number of underground works have been explored including the Pliocene clays of the ENEA underground experimental laboratory in Sicily.

The case of a tunnel that was excavated in the Laga formation of Miocene age provides an example. This formation was encountered during the construction of the Carrito tunnel of the Rome-Pescara motorway (Figure 11.2). The tunnel runs in a westerly direction through the Laga formation in its more argillaceous facies. In this area, the flysch is overthrust by a Paleogenic marly limestone that is water bearing. The whole area has been affected by tectonic disturbances with well developed fractures and faults that give the clay a scaly texture.

In spite of this tectonic activity, the various dislocations have not caused any recognizable changes either in the geotechnical behavior of the clay or in its water percolation. Indeed, the records indicate that during excavation the Carrito tunnel was completely dry until the clay-limestone contact (Figure 11.2) was reached. At this point, the overburden is 300 m thick. In this and numerous other cases that have been explored, the penetration or seepage of water from the land surface has been demonstrated to be only a few meters. This depth of penetration is normally affected by open fractures.

11.4.2. Observations at Ground Surface

Indications that permeability in clay can be induced by tectonics may be obtained directly from field observations of the distribution and intersection of yellowish-ocherous bands within the otherwise grey clay layers. As explained below, faults and fractures behave differently with regard to the penetration into a clay body of oxidizing water from the surface.

Figure 11.3 illustrates normal faults and fractures intersecting the Narni sand-clay series (Brondi and Polizzano, 1986). The total absence of traces of oxidation along the sides of the fault planes in data collected to date indicate the clay impermeability to water and therefore the property of self-sealing. By contrast, the many fractures in the main mass of the clay have oxidized edges 1 cm thick. As shown on Figure 11.4, these fractures as a rule involve no displacement; they merely run downward for tens of meters before terminating (Brondi and Polizzano, 1986).

The most likely explanation for the genesis of such fractures is that tectonics and orogenic uplift cause the clay deposits to be broken up. The disappearance of overlying as well as lateral rock masses due to erosion determines the amount of decompression in the clay, and this leads to an expansion in volume without a parallel increase in mass. This causes latent fractures to open, which induces a permeability enhancement and enables surface waters to penetrate the clay mass. However, secondary permeability due to fracturing seems to be effective only in the very uppermost part of clay masses in formations undergoing orogenic uplift and erosion.

11.5. Physicochemical Characteristics of Clay as a Factor in Radionuclide Immobilization

The oxidation-reduction potential has a significant influence on the physicochemical conditions controlling the mobility of radionuclides. Clays and sands not containing oxygenated waters have very low, to decisively negative Eh values. The consequent reducing condition insures the immobility of many radionuclides. In particular, the actinides display a geochemical behavior very similar to that of uranium and develop stable forms within the geochemical environment of clays. This fixation is therefore one of the major advantages in using clay formations as a repository for long term disposal of radioactive waste.

Exposure to the atmosphere and penetration by oxygenated waters may turn the natural reducing condition in clay to an oxidizing one. Therefore, the geochemical barrier to the migration of radionuclides may be weakened. In practice, however, the limited permeability and porosity of clay restrict, to some extent, the likelihood of this taking place. In situ observations in Italy have demonstrated that the oxidizing effects of the external environment on clay are somewhat limited even in cases where there is a high degree of exposure. Indeed, only in the upper few centimeters of clay is the original grey color normally turned to yellow as a result of the oxidation process.

Uplift of a clay-sand series in a continental environment and the consequent processes of erosion cause oxygenated meteoric waters to penetrate the permeable sandy layers that normally overlay the clay series. As a rule, however, only the thickness of the sand affected by seasonal and climatic fluctuations of the water table is oxidized to any significant degree. Below the lowest level that the water table reaches, the sand retains its original grey color testifying to the fact that reducing conditions can still persist even in a continental environment (Figure 11.5).

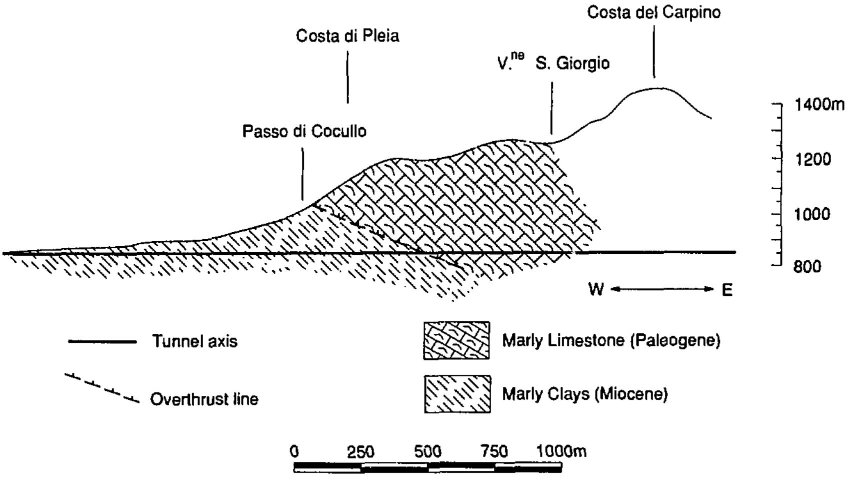

Figure 11.2. Carrito tunnel on the Roma-Pescara highway.

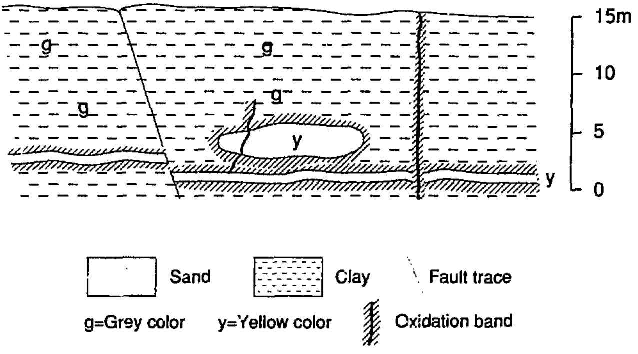

Figure 11.3. Nami clay series. Oxidation bands in clay develop along fractures and boundaries of sand lenses. No oxidation exists along the true fault.

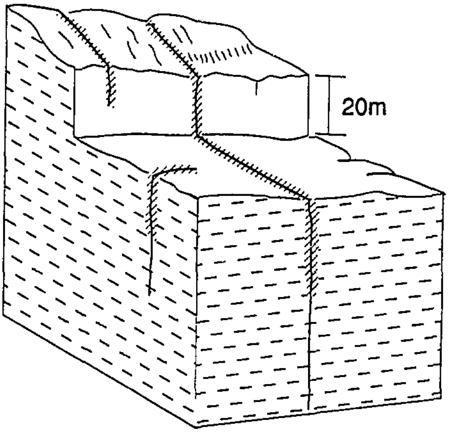

Figure 11.4. San Quirico d'Orcia quarry. The oxidation band along fractures stops some tens of meters below the surface.

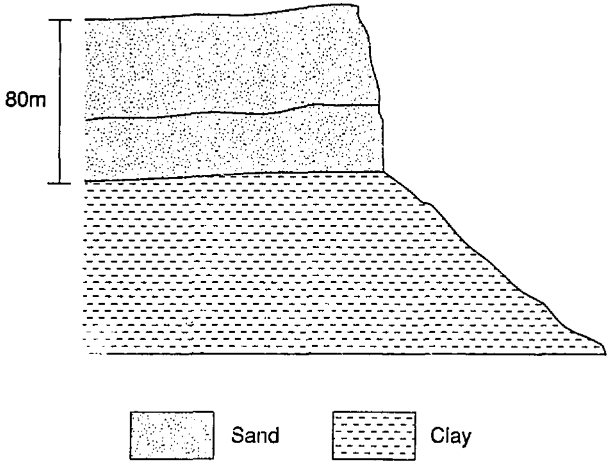

Figure 11.5. Vertical section at Volterra. The lower part of sandy deposits still shows the grey colour inherited from the original reducing environment.

The upper part of the Orte clay series of Pliocene age in the Tiber valley (Figure 11.6) is made up of a massive layer of clay and an overlying sequence of sand interbedded with clay. The sand sections are completely oxidized, yet the grey color in both the massive clay layers and the very thin clay seams within the oxidized sand indicates the persistence of a reducing environment (Brondi and Polizzano, 1986). Geochemical analyses that have been carried out (Brondi and Polizzano, 1986: Brondi et al., 1985) do not show significant differences between the content of trace elements in the main clay body and that of the thin layers interbedded with the oxidized sand. The same can be said for some of the organics that are present. The reducing environment in clays, as illustrated by this example, is essentially due to the presence of organic substances in rocks of this kind and to the capacity of such rocks to isolate these substances because of its inherent impermeability.

It is concluded that all the observations that have been made on the evolution of clay formations point to the fact that any significant alteration of the physical or physicochemical barriers would only be due to unfavorable circumstances affecting the whole geologic environment of which the clays are part.

11.6. Resistance to Heating and Effective Containment Capacity of Clay Demonstrated by Case of Magmatic Intrusion

The metamorphic halo induced in argillaceous sediments by the selagitic subvolcanite of Orciatico in Tuscany demonstrates an extreme effect of natural heating on clay (Figure 11.7). A small mafic (Fe-Mg rich) body of alkali-trachyte was emplaced underground in plastic Pliocene clays about four m.y. ago (Leoni et al., 1986). This intrusion represented a heat source that could interact with argillaceous materials for time periods of the same order as those expected for a high level radioactive waste repository.

Dramatic physical effects occurred at the contact with the subvolcanic body, as evidenced by the presence of a narrow thermometamorphic halo of thermantite. Despite these effects, the clay still maintains its original characteristics not more than 16 m from the contact. On the whole, its property as a barrier remains unchanged. Although available data do not allow an exact evaluation of depth, many features of the Orciatico igneous body (widespread glass, highly vesicular peripheral facies, etc.) suggest a shallow emplacement comparable with that usually considered for a repository. Temperatures over 800°C may be assumed from the distinctly magmatic composition of this alkali-trachyte intrusion (Barberi and Innocenti, 1967). This value is, of course, much higher than the 100°C or so that is expected around a radioactive waste site. Thus, the intrusion of the Orciatico magmatic body demonstrates the effects of an extreme worst case with reference to the temperature effects in a repository.

The mineralogical changes induced in the Pliocene clays by thermometamorphism may be generalized as follows:

(1) crystallization of pyroxene, Na-Ca plagioclase and biotite in the zone closest to the contact (hornfels facies zone);
(2) crystallization of albitic plagioclase in the colder zones further from the contact, where Na gains still occurred;
(3) crystallization of K-feldspar, most probably in more than one structural form all over the metamorphic aureole, and in greater amounts wherever significant K gains occurred; and
(4) crystallization of smectite throughout the metamorphic halo.

The argillaceous sediments around the Orciatico subvolcanite have been affected by the following physical, chemical and mineralogical transformations:

(1) Physical transformations, caused by the conspicuous recrystallization, consist mainly of a sharp loss of plasticity and of the formation of very hard rocks closest to the contact. Farther away, the clay is transformed into an indurated scaly shale.
(2) Chemical transformations consist mainly in an important migration of highly mobile elements such as alkalis (Na, K) and alkaline earths (Ca, Ba, Sr) as a result of hydrothermal circulation. In the Orciatico structure, the zones affected by cation migration appear to extend for distances up to 15 m, which was found for Na in one profile.
(3) Mineralogical transformations are mainly the destabilization of the original clay minerals (illite, vermiculite, chloritic intergrades and interstratified illite/smectite) leading to crystallization of smectite and feldspars.

The relatively large amounts of smectite explain the high cation exchange capacity observed in the metamorphosed clays; in fact, these values are

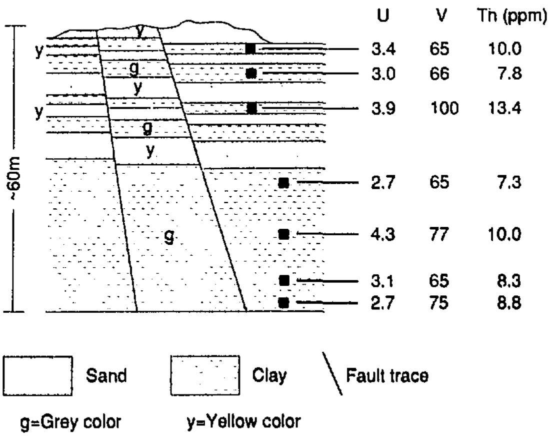

Figure 11.6. Orte clay series. No significant variation in the content of some trace elements differentiates and massive lower clay deposit from the thin upper clay levels interbedded with oxidized sandy banks.

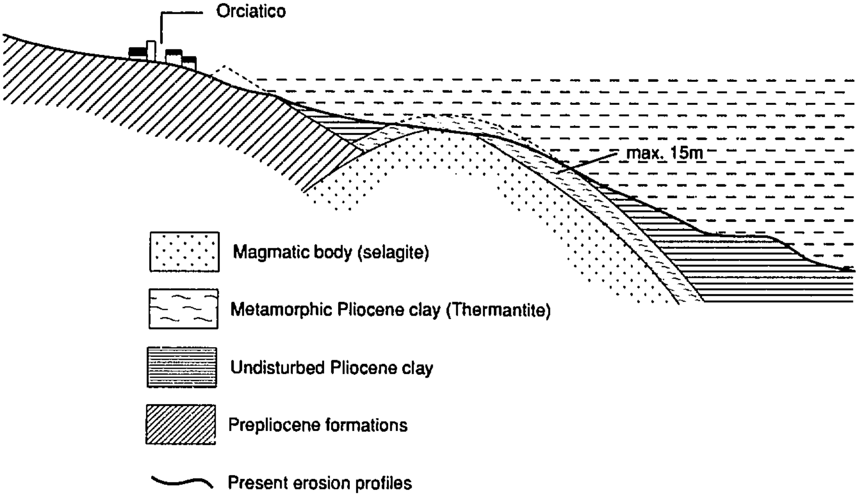

Figure 11.7. Simplified geological sketch of Orciatico subvolcanic body in clay and the related thermal halo.

similar to, or even higher than, those of non-metamorphosed sediments. The formation of smectite seems to provide positive information about the thermal stability of bentonites that are often proposed as backfill material in nuclear waste repositories (Dayal and Wilke, 1982).

Attention must be paid to the following points:

(1) The relevant size difference between the two heat sources, which obviously affects the heat released. The Orciatico subvolcanite volume is probably 10^6 to 10^7 m^3, whereas the clay repository at Mol in Belgium will have a total volume of 1,000 m^3 of vitrified waste after 30 years (Bonne and Heremans, 1982).

(2) The difference in the maximum temperatures; 800°C and above at Orciatico versus 100°C at a radwaste repository (Dayal and Wilke, 1982). This affects the thermal gradient and the dimensions of the metamorphic halo.

(3) The probable differences in the importance of fluid circulation, which is the main cause of chemical mobilization around the heat source. In the Orciatico structure, the fluid circulation was induced by a high thermal gradient that was further enhanced by the growth of a diffuse microcracking. Such an effect is probably much less important in a radioactive waste repository where mainly, thermally induced mechanical cracking and hydrofracturing from an expansion of pore fluids can be produced.

11.7. Long Term Isolation Capacity of Clay Demonstrated by Fossil Forest of Dunarobba

This final section provides information on a very significant discovery with regard to the isolation capacity of clay. The excavation of this material in the Dunarobba quarry in the Tiber valley near Terni in central Italy has uncovered some tens of tree trunks. The host rock is a lacustrine clay of the upper Villafranchiano, which was deposited about one and a half million years ago. This discovery is extraordinary from several points of view:

- the trunks are still in their original orientation; that is, they are still standing vertically (in reality, subvertically), rooted and distributed as they once were in the ancient forest;
- examples of such a remarkable number of fossil trees in physiological position are rather rare in the literature;
- in spite of the very long period of burial, the trunks are still made of wood; and
- the original ligneous structure has been perfectly preserved.

As to size, the remnants of a single trunk may exceed 1.5 m in diameter and 8 m or more in height. Much larger specimens were found years ago elsewhere in the same region (Figure 11.8). The botanical classification that has been made for fossil trees in this region (Follieri, 1977) would indicate a tropical species, such as Taxodium sp. and Nissa sp., that no longer live in Europe.

In every case, the hydrogeological isolation and/or the geochemical barrier within the clays at Dunarobba assured the preservation of the perishable organic matter. The clay beds containing the tree trunks are overlain by sand deposits in which oxidizing waters freely circulated for a long time. The thickness of the clay layers covering the tree levels doesn't exceed a few to a few tens of meters. Moreover, the whole geologic environment has been subject to regional uplift, erosion and circulation of oxidizing water in the sandy layers that overlie or are interbedded with the clay deposits. Such a situation should be considered as generally unfavorable for the preservation of this ligneous material. The fact the tree trunks still exist in such a remarkable state of preservation is due to the host clays that behave as a perfect medium of isolation.

11.8. Conclusions

The most significant factors on which the isolation capacity of clay can be evaluated are: the *physical* barrier and the *geochemical* barrier. Observations on natural parameters, the controlling factors, the environmental conditions and the evolution processes have been conducted on a time-space scale that is the same or greater than that involved in waste disposal.

The physical barrier is mostly the result of the very low permeability of clay. Faults and fractures caused by tectonism are believed to give rise to a secondary permeability in clay. Faults are very seldom observable on the ground surface; fractures, on the other hand, are frequently revealed by oxidation bands. Both are normally visible on clay walls in quarries and tunnels. Extended observations at the ground surface and in tunnels have unequivocally demonstrated that seepage of water in clay layers extends for only a few tens of meters from the surface. Ochre colored edges along fractures give evidence that in the geologic past, penetration from the surface

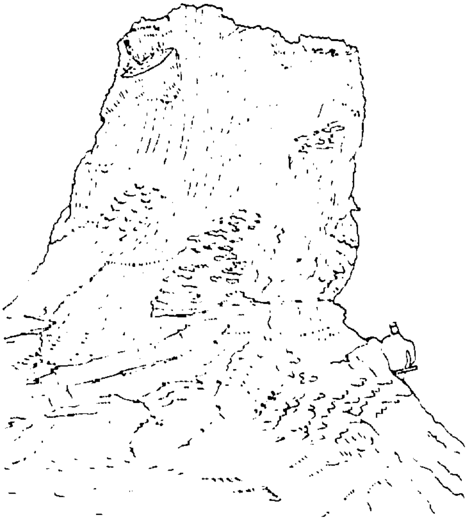

Figure 11.8. Tree trunk in fossil forest of Dunarobba. This enormous trunk has been preserved for about 1,500,000 years by clay. Now it is destroyed. At the moment of its discovery it was still wooden and it maintained its physiological structure and position (Todi quarry, Tiber Valley).

of phreatic waters with an oxidizing capacity has been more or less to the same extent. On the contrary, fault planes are always free from chemical alteration caused by this kind of water penetration. Self-sealing of fault planes may be a possibility when some sliding occurs. This could explain the differences in the hydraulic behavior of faults and fractures. From direct observation, it would appear that an oxidized fracture is always connected to a deeper unaltered fracture.

From field observations, it seems that decompression phenomena in the near-surface cause the latent fractures to be opened to penetration by groundwater. The sequence of the phenomena involved is the following: tectonic stresses induce faults and fractures in the clay; regional movements uplift the formations; erosion eliminates or simply reduces the lithostatic load on the fractures; and the near surface fractures become opened to water infiltration.

The study of natural tracers of deep origin demonstrated that a clay formation behaves as an impermeable mass. The migration of carbon dioxide, mercury and geothermal fluids, in a very hot and highly pressurized condition, is always confined to the edges of the clay basins where both the thickness and homogeneity of the clay layers are weakened or have disappeared. The magma intrusion in clay at Orciatico is a demonstration of the containment capacity of clay under extreme conditions of a dramatically active body. The clay is heavily modified at the local contact with the intrusion, but is completely unaffected only a few meters away.

The lack of traces of fluids or gases in transit through the clay surrounding the subvolcanic body and the modified clay testify to the almost complete impermeability of this argillaceous material. Among the natural tracers of deep origin, helium is the only natural element with the ability to migrate along fractures and faults. However, large masses of clay that are unaffected by recent tectonics have proven to be an absolute barrier to penetration by helium. The fact that a fossil forest still exists inside a clay mass surrounded by aggressive oxidizing waters is further evidence of the remarkable effectiveness of clay to act as both a physical and geochemical barrier of impermeability. If exposed to oxidation, the still woody trees would have been destroyed in a relatively short period of time.

The geochemical barrier is the result of two principal factors: the exchange capacity and the physicochemical conditions. With regard to the former factor, it must be kept in mind that each transformation from one clay species to another (i.e. from illite to smectite) could represent a variation but does not necessarily mean a significant decrease in exchange capacity. The normal physicochemical conditions of the clay medium correspond to a very low, or even negative, redox potential (in other words, a reducing condition). Clays acquire this chemical condition at the time of sedimentation on the sea bottom. This accounts for their capacity to immobilize the long-lived radionuclides, such as the alpha emitters (Pu, Am, Np, etc.).

Exposure to atmospheric oxygen and surface waters may change the reducing into an oxidizing environment. Such a change would tend to mobilize the radionuclides. As demonstrated from field observations, oxidation has a significant effect within the sandy layers that overlay or are interbedded with clay formations as well as on the surfaces of fractures. The oxidation is a result of an alteration due to external factors, such as uplifts, faulting and fracturing, but the extent of the effect is always just a few centimeters thick. Beyond this region, the geochemical barrier is unchanged. On the other hand, it is well known that deep subsurface waters may also display a reducing behavior as well. Fossil evidence in Italy has demonstrated that a reducing environment may also exist above the top of a clay series and may therefore serve as a supplementary geochemical barrier to radionuclide migration.

In conclusion, the physical and geochemical barrier effect displayed by clay is a general characteristic of this kind of rock. Its effectiveness as a barrier may be considered to be greater, and almost absolute, in the case of deeply buried clay. Only movement of the host clay in the surface zone as a result of general uplifting with respect to sea level and the consequent erosion may affect this barrier capacity. Of course, uplift may cause the direct destruction of the waste repository. Geochemical destabilization due to effects of oxidation would be the immediate precursor of the physical destruction. Therefore, erosion remains the principal destructive agent to be seriously considered.

The selection of sites that would be suitable for the construction of waste repositories must be based first and foremost on a thorough examination of external factors and their possible effects. As shown in Figure 11.9, subsiding zones correspond to the best situation for disposal, and stable zones are surely acceptable. Uplifting zones are not to be excluded, in principle. However, in such cases, the regional uplifting and the effects of the consequent erosion must be accurately quantified relative to the time required for waste confinement. Appropriate investigations must be carried out in order to select the most homogeneous rock masses that have been least affected by tectonic disturbances. The absence of helium in soils, boreholes and tunnels may help in localizing the most suitable situations.

11.9. Acknowledgements

We gratefully acknowledge the assistance of Mr. S. Orlowski, Head of the Nuclear Fuel Cycle and Radioactive Waste Division of the Commission of the European Communities (CEC) for his appraisal of the ENEA research program and for his encouragement to publish the present work, and Mr. B. Come in the same division of CEC for his support of ENEA activities in the field and for his critical review of this work. This work is an extended summary of a CEC report, "Natural Analouges and Evidence of Long-Term Isolation Capacity of Clays Occurring in Italy," EUR 11896 EN by F. Benvegnù, A. Brondi and C. Polizzano; PAS-ENEA, Italy, ECSC-EEC-EAEC, Brussels-Luxembourg, 1989.

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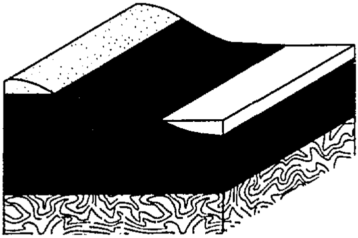
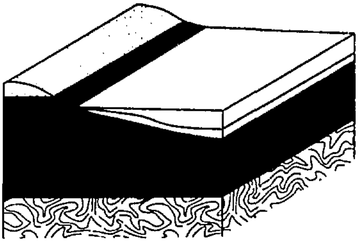
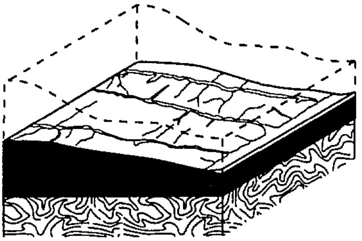


The waste repository is constructed in a geologically stable condition. The normal geomorphological evolution does not significatively affect the deposit safety.



The waste repository is constructed in a subsidence geological situation. The deposit isolation and safety are increased by the new added sediments.



The waste repository is constructed in a situation of regional orogenic uplift (or of accentuated sea regression). The erosion rate of the landscape must be accurately calculated and compared with the necessary isolation period of the waste repository.

Figure 11.9. Persistence through time of a waste deposit in clay. The intrinsic isolation capacity of clay has been demonstrated by means of natural evidence. Therefore the safety of a waste repository built within clay chiefly depends upon the general geological evolution. Three cases are possible as shown above.

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Chapter 12

Review of Geological Problems on Radioactive Waste Isolation in Japan

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12.1. Abstract

The first commercial nuclear reactor in Japan commenced operation in July 1966. Since then, 36 reactors have been put in operation and by 1988 were generating about 28 GWe, which amounts to approximately 30 percent of the total electricity supply.

A variety of radioactive wastes has been generated from the nuclear fuel cycle. Liquid wastes from the reprocessing plant are classified as high-level radioactive waste (HLW), and the other types of radioactive waste from nuclear facilities are classified as low-level waste (LLW). By the end of March 1988, the volume of LLW produced in Japan had reached the equivalent of 710,000 drums of 200 liter capacity. The preferred method of disposal for LLW is shallow land burial. A LLW disposal facility is scheduled to commence operation around 1991 in Rokkasho Mura, Aomori Prefecture. HLW is currently stored at the reprocessing plant in liquid form and is to be vitrified into a stable solid. By the year 2030, the volume of such vitrified HLW will be equivalent to 40,000 canisters of 110 liter capacity. After 30 to 50 years of cooling, the HLW is to be disposed of in geological formations deeper than several hundreds of meters ("geological disposal").

In order to realize the geological disposal system, it is necessary to identify the long-term safety of the system through performance assessment and feasibility of construction of the facility. It is also necessary to develop site characterization techniques that take into account the natural characteristics of Japan such as the active groundwater flows resulting from the topography and the geotectonic issues due to the Circum-Pacific Mobile Belt. *In-situ* investigation is essential to provide data and knowledge on the relevant geologic environment for the evaluation of safety and feasibility of the disposal system and to develop methods and instrumentation for site characterization. A regional survey for candidate site selection has been conducted on geologic stability, hydrogeological and geochemical properties, and crustal movement during the Quaternary period.

In-situ experiments have been carried out in galleries and boreholes for the purposes of hydrogeology, geochemistry and geomechanics. Hydraulic parameters that will contribute to the development of a predictive model of groundwater flow are measured in deep boreholes. Borehole logging is carried out to characterize the physical properties of rocks and the details of fractures such as the distribution, density and filling materials. Geochemistry of deep groundwaters is investigated with regard to redox potential and rock-water interactions. Isotope geochemistry is being used to determine age and origin of deep groundwater in support of the groundwater flow model. Special instruments have been developed for the hydrogeological and geochemical investigations. Mine-by experiments on excavation responses are in progress, and geomechanical data have been obtained to evaluate responses. An investigation on radionuclide migration of the natural U-Th series is being conducted in a uranium deposit for a natural analogue study. This is expected to contribute to the problem of validating migration models for performance assessment. It is also important to

evaluate the effect of crustal movement on isolation performance of the disposal system. Seismic transmission measurements at several levels in galleries in an old mine have been made for this purpose. Furthermore, neotectonics has been studied to develop methods for evaluating long-term safety of the system.

12.2. Introduction

The first commercial nuclear reactor in Japan commenced operation in July 1966. Since then 36 reactors have been put in operation and were generating about 28 GWe by 1988, which amounts to approximately 30 percent of the total electricity supply. By the year 2000, nuclear power generation in Japan is expected to reach 53 GWe, or 40 percent of the total electricity supply.

A variety of radioactive wastes has been generated from the nuclear fuel cycle. Liquid waste from the reprocessing plant is classified as high-level radioactive waste (HLW). Other types of radioactive wastes that are generated by nuclear facilities such as power plants, large research facilities, the uranium fuel fabrication plant, and the reprocessing facility are classified as low-level waste (LLW).

Japanese policies concerning the treatment and disposal of radioactive waste are in accord with the, "Long Term Program for Development and Utilization of Nuclear Energy," which was established by the AEC (Atomic Energy Commission of Japan). The new version of this program was drawn up in 1987. To further promote these policies in detail, discussions were held by the Advisory Committee on Radioactive Waste Management of AEC. As a result, two reports were published in August 1984 and October 1985, with concrete programs for the actual processes and steps to be taken in the land disposal of LLW. These were in accordance with the level of radioactivity and the responsibility of sharing as well as the establishment of a practical system for the treatment and disposal of radioactive waste. In December 1986 following the above reports, STA (Science and Technology Agency) set up a "Five Year Program for Research and Development on Geological Disposal of High-Level Radioactive Waste," as a concrete program.

12.3. Policy for Disposal of Radioactive Wastes

12.3.1. Low-Level Waste

The 50,000 drums of 200-liter size of LLW that are produced annually by Japanese nuclear facilities are kept in safe storage after they have been conditioned. By the end of March 1988, a total of 710,000 drums had already accumulated. The preferred method of disposal for LLW is shallow land burial. At present, the Japan Nuclear Fuel Industries Ltd., made up mainly of Japanese utilities, is promoting concrete plans for a centralized burial facility for LLW. This facility is scheduled to commence operation about 1991 in Rokkasho Mura, Aomori Prefecture, in the northern part of the main island of Japan.

12.3.2. High-Level Waste

HLW is currently stored at the reprocessing plant in liquid form and is to be vitrified into a stable form. By the year 2030, the volume of such vitrified waste will be equivalent to 40,000 canisters of 110 liter capacity. After a 30 to 50 year period of cooling, the HLW is to be disposed of in geological formations deeper than several hundreds of meters ("geological disposal").

12.4. Natural Features and Research and Development Target in Japan

The Japanese islands are situated along the northwestern marginal parts of the Pacific and Philippine Sea plates as part of the Circum-Pacific Mobile Belt. This plate system was formed at the beginning of Neogene time. Geological and geophysical events such as volcanism, earthquakes, gravity anomalies and crustal movements reflect the effects of the system on the area around the islands. Though the geologic structure that was formed is apparently complicated, it is basically in a belt along the island arc.

The geotectonics is divided by two main tectonic lines. One is the Median line that is considered to have been formed 80 m.y. ago. At present, it is sometimes partially active along a line running in an east-west direction through the southwestern part of Japan. The other is Fossa Magna of Neogene time cutting central Japan into two parts in the north-south direction. In addition, the Tanakura tectonic line is believed to be a major discontinuity in the basement in the northeastern part of the main island.

Except for rock salt, which is not found in Japan, most of the rock types are distributed in small bodies. The amount of outcrop areas for the various rock types are given in Table 12.1. The large amount of Cenozoic outcrops, especially the volcanic and sedimentary rocks in and after Neogene time, reflects the effects of the present plate system. Physical properties differ significantly between Paleogene and Neogene rocks. The Paleogene rocks are highly consoli-

Table 12.1. General Geology of Japan (after Doi and Hirono, 1987)

Geology			Area		Lithology
			km^2	%	
Sedimentary Rocks	Cenozoic	Quaternary	73,112	19.3	ss, m, c, s, ga
		Tertiary	73,269	19.4	ss, m, c, sh
	Mesozoic		30,270	8.0	ss, sh, sl, c
	Palaeozoic		43,869	11.6	ss, sl, t, l, c
Cenozoic volcanic rocks			82,769	21.9	a, b, r, t
Acidic effusive rocks (Cretaceous)			17,708	4.1	r, t
Acidic intrusive rocks			39,408	10.4	gr, g
Basic intrusive rocks			4,517	1.2	g, d
Metamorphic rocks			15,640	4.1	gn, sc
Total			378,562	100.0	

Note:
a = andesite;
b = basalt;
c = conglomerate;
d = diabase;
g = gabbro;
ga = gravel
gn = gneiss;
gr = granite;
l = limestone;
m = mudstone;
q = quartz porphyry
r = rhyolite
s = sand
sc = crystalline schist
sh = shale
sl = slate
ss = sandstone
t = tuff and tuff breccia

dated and fractured while the Neogene are consolidated but less fractured. Most of the Neogene volcanics, called "green tuff", are altered and contain zeolite and clay minerals. The acidic intrusive rocks, most of which are Cretaceous to Paleogene in age, are mainly granitic, usually fractured and partly weathered. The oldest rocks of the Paleozoic are Ordovician; the majority are Permian in age. The Paleozoic rocks are usually highly fractured granites.

There are many kinds of ore deposits in Japan, though generally the ore bodies are small. There are deposits of both ferrous and non-ferrous metals, such as Ag, Au, Cu, Mn, Pb, U and Zn, and there are also deposits of coal and oil. The islands are active with frequent volcanism and earthquakes. The country belongs in the Temperate zone with a mild and humid climate and considerable rainfall. Mountainous regions occupy more than half of the country.

Geologic formations in such a tectonic environment are sometimes perceived to be physically unstable for the isolation of radioactive wastes. Since the geological disposal system is also considered as a chemical system (SKB, 1983), the formations to be used in the disposal scheme must also be evaluated from the geochemical standpoint. Fritz and Frape (1987) recently pointed out that the assumption that crystalline rocks in the Precambrian shield are non-reactive and thus suitable for waste isolation is not justified from the viewpoints of hydrogeological and geochemical studies. Further investigations are needed to examine the meaning of "suitable" for waste disposal schemes.

We believe the geological environment in Japan is suitable as a host media for the concentration and preservation of elements, as is suggested by the presence of uranium and other ore deposits. It is, therefore, important to investigate hydrogeology, geochemistry and radionuclide migration in relation to the effects of crustal movements, such as earthquakes and faulting, in order to evaluate the feasibility of the disposal scheme.

Much rainfall and high temperatures play a significant role in the recharge of groundwater; of course, the effects of river flows and evapotranspiration must be taken into account. Recharge of groundwater from the surface to the underground does not occur uniformly everywhere reflecting the effects of topography. This has to be considered in groundwater model development.

12.5. Current Research and Development Program in Japan

One of the major activities is to achieve a firm scientific and technical background on which the Japanese concept for geologic disposal of HLW can be based. Several *in-situ* experiments in different rock types have been carried out. The main objectives are summarized in an OECD/NEA (1988) report:

(1) development of methods and instrumentation for specific site investigation and characterization techniques,

(2) provision of field data to facilitate the validation of process and performance assessment models,

(3) provision of data in support of the groundwater model, and

(4) evaluation of the engineering feasibility of the construction, operation and closure of the repository.

An extensive research and development program is in progress in the Tono area in the central part of Japan. This study area includes an experimental uranium mine with no commercial production history. The mine shaft and galleries are well maintained to provide an appropriate environment for various experiments. The discussion below outlines the current status of the R&D effort in the Tono area.

Another *in situ* research and development site is in the Kamishi area in the northern part of Japan where an initial series of tests have now been completed in and around an iron mine in the crystalline basement.

12.6. Current Status of In-Situ Experiments

12.6.1. Geology

In the Tono area, sedimentary rocks of Neogene-Quaternary age overlie Cretaceous granite unconformably (Sakamaki, 1985). The sedimentary rocks are classified into three units: Seto G. (Plio-Pleistocene), upper Mizunami G. (Miocene), and lower Mizunami G. (Miocene). The Seto G. unit is unconsolidated and has a high permeability. The lower Mizunami G. contains a uranium ore body, which is cut by a reverse fault. Depth to the uranium deposit is less than 150 m, and a shaft and gallery have been constructed in the middle part of the ore body.

12.6.2. Hydrogeological Investigations

In making a hydrogeological evaluation of a site, it is essential to investigate the regional hydrology prior to making a detailed study within the site. Though hydrogeological structures are usually complicated near the surface, they must be understood and included in the regional flow model. In fact, it is hardly possible to make a three dimensional analysis with only an approximation for the actual groundwater flows. Hence, it is necessary to simplify and model hydraulic conditions, such as hydrogeological structure and precipitation, while retaining the general flow system of the area. For the purposes of the analysis, it is also important to choose suitable boundary conditions and hydraulic parameters that are representative of the real situation. The following three items must be established for the analysis:

(1) numerical model for the hydrogeological structures based on data from geological, geophysical and borehole drilling,

(2) hydraulic conductivities for saturated and unsaturated zones plus pore pressures from hydraulic testing in drill holes,

(3) measurements of river flows, rainfall and evapotranspiration in field surveys.

12.6.3. Hill Slope Hydrology

In the Tono area, surveys have been carried out on surface layers with their natural water in order to determine the amount of groundwater recharge from rainfall. The following studies are in progress:

(1) lineament analysis on Landsat photographs,

(2) vegetational and morphological analyses on aerial photographs,

(3) drainage interpretation,

(4) hydrogeological interpretation,

(5) surface hydraulic characterization of river flows, precipitation and evapotranspiration,

(6) measurement of specific discharge and electic conductivity.

Lineament analysis on Landsat photographs is available to delineate hydrogeological units according to their distribution patterns. The distribution of vegetation is recognized as reflecting hydrogeological differences. Because most river water in the dry season is considered to be groundwater, river flows are measured in each drainage valley during that season to investigate the relationship between geology and the amount of water. As a result, the Seto G. area, which has a high permeability, was found to have a high storage capacity.

12.6.4. Hydrogeological Characteristics

Groundwater flow in granitic rocks is influenced by the fracture system, and it is necessary to understand the distribution and characteristics of this system in the analyzing the flow. An investigation has been carried out in the fracture system of the Tono area in several drill holes that reached a maximum depth of 1,000 m in granitic rocks. Based on core observations, most of the fractures can be classified as being: planar, irregular, curved or stepped.

The *planar* type, with a higher angle, has a smooth surface with striations and is sometimes filled with chlorite, sericite and calcite. The *irregular* type is characterized by a rugged surface without striations, usually some clay minerals, and has both higher and lower angles. The *curved* type has curved fractures and occurs only rarely. The *stepped* type has stepped fractures on the fracture surfaces. Each type has a distribution of density and filling materials along the depth of the drill hole. At present, the relationship between the filling materials and the fracture patterns is being examined.

Hydraulic tests have been carried out in the same drill holes to obtain data on hydraulic parameters and to understand the relationship between these parameters and the distributions and characteristics of fractures in granitic rocks. In some drill holes, the pore pressures show a hydrostatic distribution that is compatible with the observations on cores that vertical fractures are a predominant feature. This suggests that groundwater passes vertically through the fracture system.

Hydraulic conductivities are approximately 2.4×10^{-8} cm/s in the fracture-poor sections of the core and approximately 2.1×10^{-4} cm/s in the fracture-dominant parts. The hydraulic conductivity is low in some fracture-dominant sections where filling materials occur in the the fractures. This means that, in modelling groundwater flow, the nature of the filling materials should be considered as well as the fractures themselves. As illustrated in Figure 12.1, the fracture permeability of these granitic rocks tends to decrease with depth, and this has been observed in other countries. Hydraulic tests are also in progress in sedimentary rocks.

Because core recovery is usually low in a fractured zone, which may be an important pathway for groundwater, it is sometimes difficult to obtain continuous data vertically. Geophysical logging can solve most of these problems, because the logging provides data that represents the physical parameters of the rock mass around the borehole. To survey efficiently, multiple logs such as micro-resistivity, caliper, electric, natural gamma, neutron and sonic have been used.

To provide reliable data for the flow model, it is necessary to know the spatial distribution of hydraulic conductivity as well as the local value measured directly in the borehole. Cross-hole radar measurements have been made in two drill holes spaced 40 m apart to investigate the heterogeneity of the fracture distribution in the granitic rocks. This is a new technique to detect fracture distributions.

A groundwater flow model has been developed for the granitic rocks in the Miocene Mizunami G. formation that includes recharge from the higher permeability, overlying Seto G. layer.

12.6.5. Hydrogeochemical Investigation

It is important to characterize the groundwater chemistry because this information is needed in such problems as leaching of glass, corrosion of overpack materials, alteration of bentonite and migration of radionuclides in a disposal system. In the early stages of site characterization, the chemistry of deep groundwater will be investigated by drilling. This will include samples of groundwater for chemical analysis and redox potential (Eh) measurement; the technology for such measurements has been under development.

This new technology has been used to gather data on groundwater chemistry using the gallery at 150 m depth and shallow drill holes in the Tono area. Groundwater and surface water samples were collected and analyzed from drill holes, the gallery and local wells. A double packer system is used to collect water samples from isolated intervals in the borehole. Uranine is used as a tracer to determine if the groundwater has been contaminated. The basis for deciding if contamination has not occurred is that as fluid is withdrawn, the concentration of uranine decreases to a low level (from 500 to 10 ppb) and the chemical composition and electrical conductivity stabilize at fixed values.

In the Tono area, the groundwaters can be classified into four groups. Three of them are from sedimentary rocks and the fourth is from granitic rock (Table 12.2). The three types of

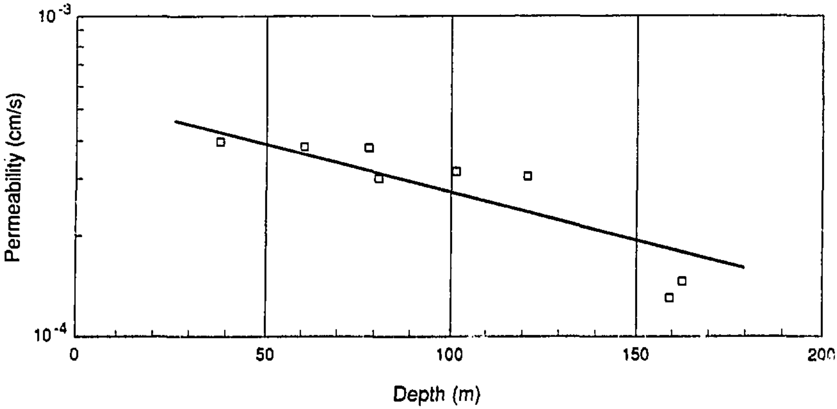

Figure 12.1. Permeability versus depth.

Table 12.2. Chemical and Isotopic Composition of Waters*

Sample No.	pH	Na (ppm)	Fe (ppm)	U (ppb)	HCO_3 (ppm)	F (ppm)	Eh (mv)	^3H (pCi/1)	δD (o/oo)	$\delta^{18}O$ (o/oo)	$^{234}U/^{238}U$
1	6.5	<1	0.3	0.1	10	0.2	-	35	-46	-7.6	-
2	6.2	2	0.1	0.1	20	0.1	-	35	-46	-7.5	-
3	7.2	18	<0.1	0.1	60	0.1	-	-	-52	-8.1	-
4	8.6	35	<0.1	0.1~1	90	3	~-300	<3	-55	-8.5	1.6~2.8
5	8.8	36	<0.1	0.1~1	80	4	-	<3	-55	-8.6	-

water correlate with the stratigraphy of the Seto G. and the upper and lower Mizunami G. The Seto G. groundwater, which is uppermost in this sequence, is similar to that of surface water, which has a lower electrical conductivity and ionic composition with a pH of 6 to 6.5. Groundwater from the lower Mizunami G. has a higher HCO_3 and Na content with a pH of 8.5 to 9.0. Groundwater from the upper Mizunami G. has a composition between that of the above two types except for the Ca content (not shown on Table 12.2), which is higher than that of the lower Mizunami G. The groundwater of the granitic rocks has a much higher HCO_3 content than that of the lower Mizunami G. The lithology of these rocks sometimes contains lignite, tuffaceous sandstone, mudstone and conglomerate with small variations, and the differences in chemical composition may represent the effects of the groundwater residence times in each of the groups.

Isotopical analyses were carried out for tritium, hydrogen and oxygen in ground and surface water samples. Seto G. water has high values of tritium, δD and $\delta^{18}O$, which are almost the same as that of surface water, while that from the lower Mizunami G. is low in tritium, δD and $\delta^{18}O$. The results for deuterium and oxygen-18 for both classes of waters fall on the line for meteoric waters as shown on Figure 12.2. It is concluded that the Seto G. water is directly recharged by surface rainfall.

However, water from the lower Mizunami G. is interpreted as being older than that of Seto G. This is suggested by the differences in chemical composition and tritium content. The values of δD and $\delta^{18}O$ are lower by 10 and 1 per mil, respectively, than those for surface water and Seto G. groundwater. Although the origin of lower Mizunami G. water is from the surface, it is clearly different from that of present day water. These important differences are being examined

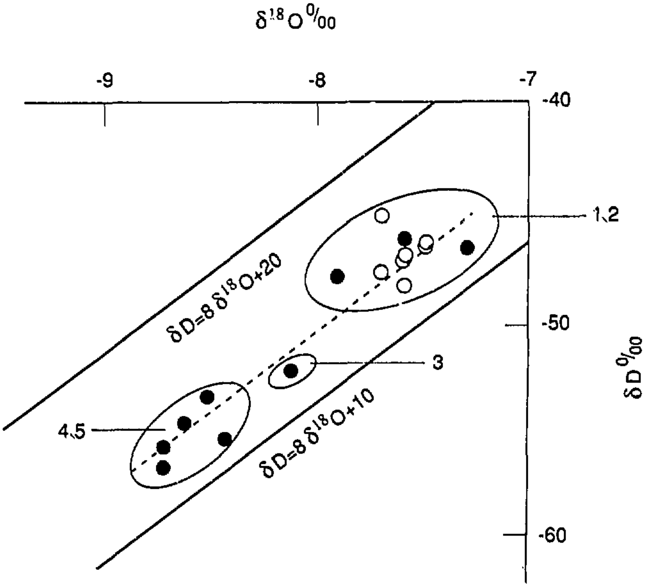

Figure 12.2. δ D vs $\delta^{18}O$ of surface and ground waters. O for surface waters and ● for groundwaters. The numbers represent the sample numbers given in Table 12.2.

to provide data that should be compatible with the model now being developed for the groundwater flow system of the area.

The methods that utilize $^{234}U/^{235}U$, ^{14}C and ^{36}Cl are currently being examined for their possible use in determining origin and age of these groundwaters. A basic experiment is also planned to determine the major effects on Eh values during its measurement prior to the construction of the needed instruments.

12.6.6. Mine-by Experiments

Excavation responses of the rock mass are a major factor in performance assessment and repository design. It is necessary to obtain data on these responses and to establish reliable methods for their prediction. Mine-by experiments are being conducted in the sedimentary rock of Tono mine with the objectives of developing instruments and methods for the measurement of rock mass behavior. The following studies are in progress:

(1) tests and measurement of rock behavior during excavation,

(2) tests and evaluation of instruments, and

(3) comparison of the actual rock mass displacement with predictions from the FEM (finite element model).

After completion of the tunnel excavation by blasting, measurements of permeability, rock mass displacement, and stress and seismic tomography were made. The results indicate that the extent of the excavation response did not go beyond 1.5 m from the tunnel wall.

12.7. Natural Analogue Study

A natural analogue study is being conducted on radionuclide migration in and around the uranium ore body in the Tono area (Ochiai et al., 1989). One of the objectives of this study is to support the validation of performance assessment. The geological environment is obviously suitable for the preservation of the existing uranium ore body, and this environment will be sufficiently characterized by the *in-situ* hydrogeological and geochemical experiments described above. The results of the analogue study are therefore expected to make an important contribution to the next step of site selection.

The uranium ore body is a lenticular deposit in the lower Mizunami G. that is 3.4 km long, 0.5 km wide and 1-3 m thick. The average ore grade is 0.06% U_3O_8, and the uranium is adsorbed on zeolite and clay minerals. Deposition of ore took place in a paleoriver system within a channel structure that dips gently to the east along an unconformity below the Mizunami G. From geologic evidence, the uranium is thought to have been concentrated as an ore after being transported along this structure by groundwater.

According to the results of hydrogeological investigations to date, groundwater presently flows along the structure from west to east, although there is vertical flow in some places. If it can be assumed that the ore migrated with the groundwater, it must have moved along the structure from the west (upstream) toward the east (downstream). This suggested that an investigation of radionuclide migration should be made Three boreholes were drilled at upstream, middle and downstream locations, and cores were collected for chemical analysis of the $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ ratios. No distinct fractionations were observed. This means that within the last one million years, the nuclides have hardly moved around this orebody, because it takes about that long to reach radioactive equilibrium for this nuclide series.

Another investigation was made to see if the scale of nuclide migration could be detected. A one meter cube of rock with a higher grade of ore was mined from the gallery and subdivided into 64 subcubes, each 25 cm on edge. Chemical analyses were made on each subcube and on one cube as described above. The results indicate that there was nuclide movement within the one meter cube but not across it. At present, it is concluded that the scale of nuclide migration, under the reducing conditions in this deposit, does not exceed a few meters. A quantitative investigation is planned to validate performance assessment in terms of groundwater flow rate.

12.8. Tectonic Environment

Tectonics plays a major role in determining the nuclide release scenario for a waste disposal system. In particular, neotectonics is important because it involves the same range of time as that envisioned for the disposal system. Investigations are being carried out with emphasis on earthquakes and faulting among the events described by IAEA (1985). In order to evaluate the influence of earthquakes on geological formations, the maximum accelerations from real events have been measured with seismographs set up at various levels in an old mine. The maximum values for the accelerations tend to decrease with depth.

A fault that is believed to have formed in an area after uranium mineralization had taken place has been investigated from the standpoints of hydrology and nuclide migration. The question has been raised whether a fault containing clay minerals can prevent groundwater flow. This means that a fault does not necessarily become a flow path for groundwater if clay minerals are formed after the fault has occurred. A preliminary survey indicates no distinct concentrations of nuclides along the fault. An investigation is currently underway to study the relationship between the fault properties and the hydrology.

12.9. Conclusions

The technology of geological disposal is being developed with the objectives of identifying the long-term safety of the system through performance assessment, feasibility of construction of the facilities and site characterization techniques. *In-situ* experiments have been carried out on hydrogeology, geochemistry and excavation response. Hill slope hydrology has been identified as an important component in hydrogeological investigations. Geochemical data that are compatible with isotopic and hydrogeological data will be used. The migration of radionuclides is being investigated in a natural analogue study. The results will be analysed in relation to the effects of crustal movements such as uplift and faulting.

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Chapter 13

Research Program on Geological Disposal of Radioactive Waste in The Netherlands

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13.1. Introduction

Two nuclear power plants are in operation in The Netherlands with a total capacity of 500 MWe. The spent fuel elements from these plants are being reprocessed. The resulting radioactive waste from these operations together with that from all other sources in this country will be stored, on an interim basis, for the next 50 to 100 years. After that, it will be necessary for part of the waste to be isolated definitively from the environment.

One of the options that has been studied during the past five years is geological disposal in the subsurface of the country itself. Other options that have seriously been considered are disposal in deep ocean sediments and disposal on an international or bilateral basis. The geological disposal will have to be effected in such a way as to insure that, after completion of the disposal operations, the waste remains isolated from the biosphere for an extended period, without future generations being required to actively manage the facility. The research program is focussed on the possibility of disposal in salt formations as they exist in the subsurface of The Netherlands. This decision has been motivated by the following reasons:

- the presence of rock salt under large areas of northern and eastern Netherlands,
- the attractive properties of this rock in relation to the final disposal of radioactive waste, and
- the availability of abundant practical experience in mining salt.

The terms of reference as set out for the first phase of the research program (1985-1989) were to acquire knowledge and understanding about the possibility of final and safe disposal of radioactive waste using current techniques of mining engineering as applied to salt formations of the nature and size of those in The Netherlands. This first phase, which has just been concluded, was comprised of laboratory investigations, literature search, model calculations and participation in foreign and international studies. The budget for this phase was US $15 million.

13.2. Content and Structure of Research

The research program has been concerned with three types of formations: bedded salt, salt pillows, and salt diapirs or domes. The main features are illustrated in Figure 13.1. A schematic model was made for each type to represent what may be expected in the subsurface of The Netherlands. These models were designed as part of the geological and geohydrological investigations.

With regard to disposal techniques, conventional mining was considered for all waste types. Also, a combination of deep boreholes for high-level-waste (HLW) and two types of caverns for medium-level waste (MLW) and low-level-waste (LLW) were studied. Pre-designs to apply these techniques in salt formations have been developed in a mining engineering study. Depths of up to 1,500 m are being considered for the conventional mine option, 2,000 m to 2,500 m for deep boreholes, 2,000 m for brine-filled caverns and 1,000 m for dry caverns. In addition, three scenarios for waste flows have been considered:

- existing power plants (500 MWe) with interim storage of at least 50 years,
- expansion of nuclear power by a total of 3,000 MWe with interim storage of at least 50 years, and

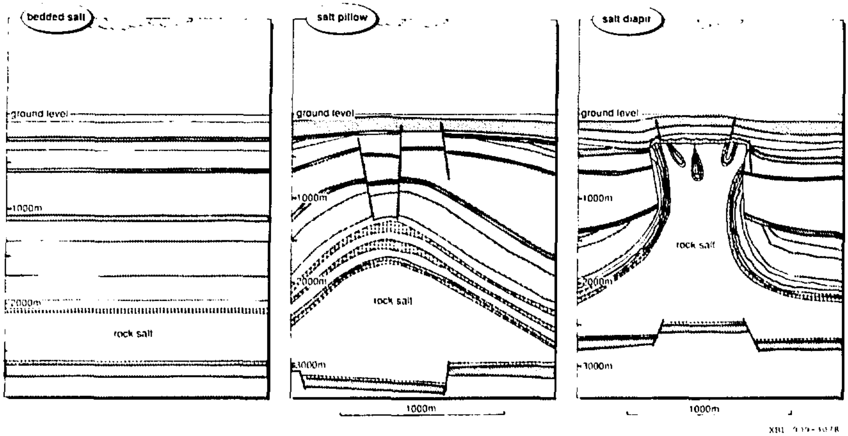
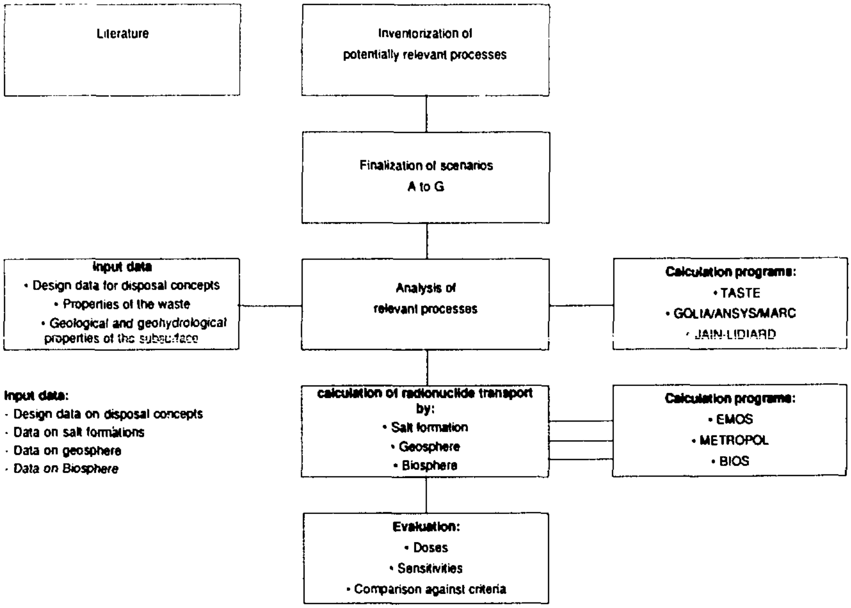


Figure 13.1. Main features of salt formations being studied.



XBL 909-3079

Figure 13.2. General structure of safety study.

- same expansion of nuclear power with interim storage of only ten years.

The general structure of the safety study that was made is illustrated in Figure 13.2. Twenty one disposal concepts were examined in this study, each of which involved a pre-design developed for a given type of salt formation in a given waste strategy. The central theme of the study was the safety that each concept would provide in the long term. In particular, the study was designed to:

- identify circumstances, processes and events that might allow radionuclides from the waste to enter into the biosphere, and
- determine the radiation doses that persons might receive as a result, and the time spans over which those doses might occur.

The safety study was not directed at particular sites. A representative model was drawn up for each formation type, based on the available geological and geohydrological data on salt formations in The Netherlands and the associated overlying strata. Special care was taken to ensure that these models do not give an over optimistic picture of the geological situations they represent.

The disposal concepts considered are based on the multi-barrier system as shown in Figure 13.3; that is to say, they are so designed that several barriers are present surrounding the waste. Radionuclides from the waste can only reach the biosphere if they can pass through all such barriers by whatever means. The protection offered by the various disposal methods and geological formations therefore depends on the combined effectiveness of the natural and engineered barriers as a whole.

Combinations of developments and events which might lead to the release of radioactive material from the waste have been identified and are referred to as scenarios. These scenarios relate to the period after the disposal facility has been sealed.

The scenarios for normal evolution are based on expectations relating to processes and events that are not to be regarded as exceptional. Each scenario serves as a model for a series of possible developments which might affect the disposal facility up to some date in the remote future. The principle scenarios in this category are concerned with diapirism and subrosion.

Allowance has also been made for processes and events in such combination or of such intensity that they will have a relatively small probability. The altered evolution scenarios were put together in this way and were developed from the standpoint that water or brine will be the principal medium of transport in the geosphere.

A third category of scenarios includes events and processes, such as human intrusion, earthquakes, meteorite strikes, etc., that could destroy the barrier system. From a literature search, it was concluded that the possibility of the waste isolation being diminished or destroyed as a result of human intrusion should be taken as the most relevant possibility for the disposal concepts under consideration. This category is referred to as disruptive events.

With the exception of just a few cases, the probability that the scenarios will occur is generally less than one. However, it was decided for practical reasons not to quantify these probabilities systematically, and therefore, the approach used here has largely been deterministic.

Repository acceptance will depend on the result of the safety analysis. A radiological criterion for assessing long-term safety of disposal concepts is currently being developed by the Dutch Government.

13.3. Release Scenarios

The release scenarios that have been developed in this safety study are the following:

- Scenario A - initiated by diapirism and subrosion. This scenario is illustrated on Figure 13.4 and proceeds on the assumption that water is not only important as a means of radionuclide transport, but also because of salt dissolution. As a result, the thickness of the salt shield around the waste can gradually diminish (process of subrosion). This phenomenon can be particularly important in combination with diapirism. In such a case, interest focuses on possible situations where the disposed waste reaches a relatively shallow depth (several hundred meters) as a result of diapirism and the salt shield is then subject to subrosion. In this scenario, it is assumed that the waste ultimately comes in contact with groundwater. To illustrate what this means, if one uses somewhat less than 0.4 mm/yr for diapirism and less than 0.15 mm/yr for subrosion, it will take about two million years for this scenario to be realized. Once groundwater (or brine) has invaded the immediate environment of the repository, the canisters will corrode, after which the waste matrix (glass) will be leached and the groundwater will become contaminated. Thereafter,

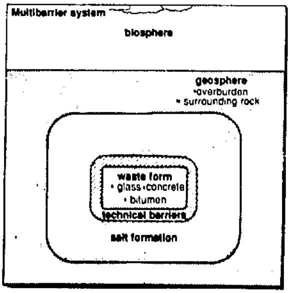


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Figure 13.3. Concept of multibarrier system.

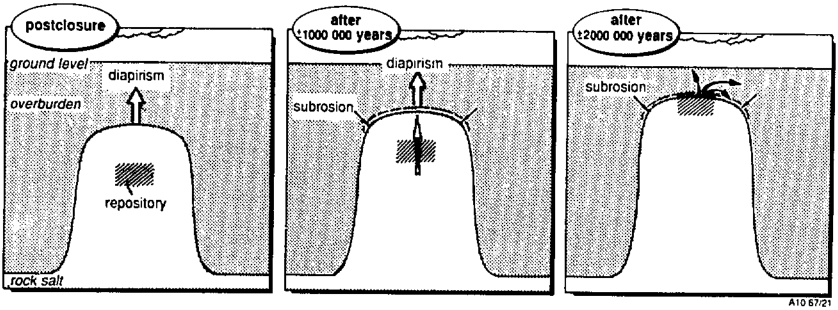

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Figure 13.4. Scenario A initiated by diapirism and subrosian.

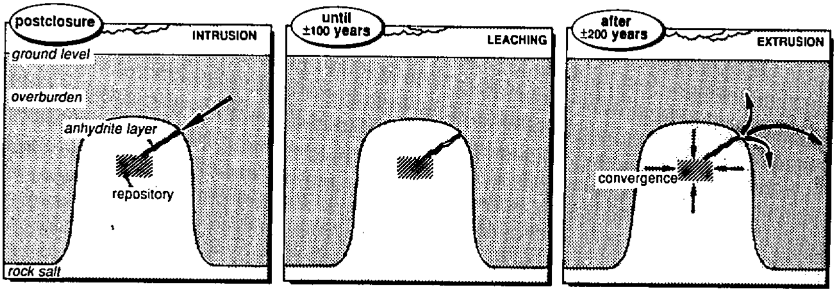

Figure 13.5. Scenario D initiated by flooding of the repository.

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1200 m on the eastern flank of Yucca Mountain, where test well UE-25p#1 penetrated the Timber Mountain Tuff, the Paintbrush Tuff, the tuffaceous beds of Calico Hills, the Crater Flat Tuff, the Lithic Ridge Tuff, the Older Tuffs, and 500 m of Paleozoic carbonate rocks (Figure 2). Bedded tuffs were encountered between each of the major tuffs.

In the saturated zone, aquifer boundaries may not coincide with stratigraphic boundaries. Results from borehole geophysical surveys and well hydraulic tests suggest that a strict hydrostratigraphic categorization based on lithology and laboratory-derived hydraulic properties inadequately represents groundwater flow at the scale of the well tests (Waddell et al., 1984). Although fractures are the principal conduit for groundwater flow in the saturated zone, borehole flow-production surveys show that the majority of fractures mapped in boreholes do not contribute to flow. Flow is typically dominated by only a few fractures or groups of fractures.

Most hydraulic tests conducted at Yucca Mountain have been single-well tests conducted in thick composite sections of borehole, and most of these have been falling-head injection tests. The pressure-transient responses for most of the tests conducted in fractured intervals of boreholes cannot be explained by linear or radial flow models. Spherical flow models (Karasaki et al., 1988) and another model based on a noninteger-dimension flow field (Barker, 1988) can explain many of the pressure-transient responses. These models indicate that the flow geometry has a fractional dimension somewhere between 2 (radial) and 3 (spherical). Several tests conducted in unfractured sections of boreholes were indicative of poorly conductive units and displayed ideal radial flow behavior for the duration of the tests. Similarly mixed pressure-transient responses have been measured in single-well tests conducted in tuffs elsewhere at the Nevada Test Site (Charles Savard, U.S. Geological Survey, oral commun., 1990).

The frequency-dependent fluid-pressure responses measured in the c-holes can be explained by water-table drainage, indicating that the monitored intervals are in hydraulic connection with the water table. For the response measured below the packer in UE-25c#3, this means that the hydraulic connection between the lower Bullfrog member of the Crater Flat Tuff and the water table near the top of the tuffaceous beds of Calico Hills is realized over the 350-m thickness of saturated tuffs (Figure 2). Estimates of vertical hydraulic conductivity made on the basis of the frequency-dependent responses in the c-holes are on the same order of magnitude as those measured in cores from nonwelded units and are about two to three orders of magnitude larger than measurements made on cores from moderately to densely welded units (Galloway and Rojstaczer, 1988). If conductive fractures alone provide the hydraulic connection between the water table and deeper stratigraphic units, the in situ measurements would be much larger than the measurements from cores, which reflect matrix properties. This suggests that the vertical hydraulic connection in the stratigraphic section penetrated by the c-holes is limited by the matrix hydraulic conductivity of the nonwelded tuffs. Taken together with other information on fracture orientation and density and fault boundaries, these results indicate that an areal two-dimensional flow

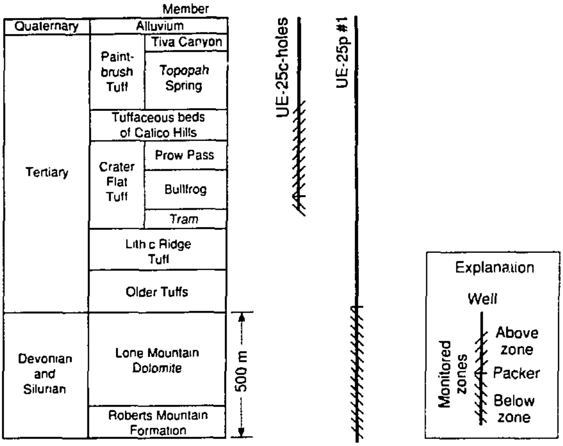

Figure 2. Schematic stratigraphic column of the rock units penetrated by UE-25p#1 and the c-holes. [XBL 913-469]

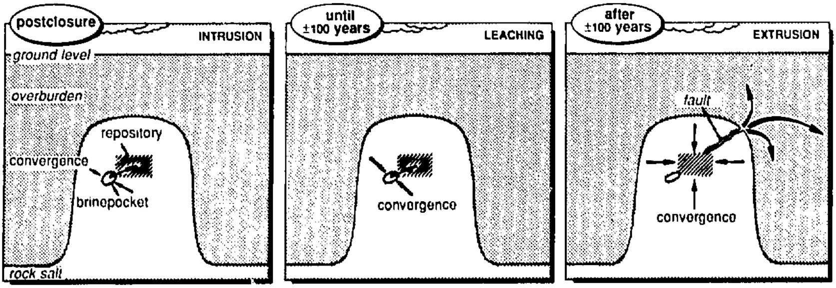

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Figure 13.6. Scenario E initiated by large brine pocket.

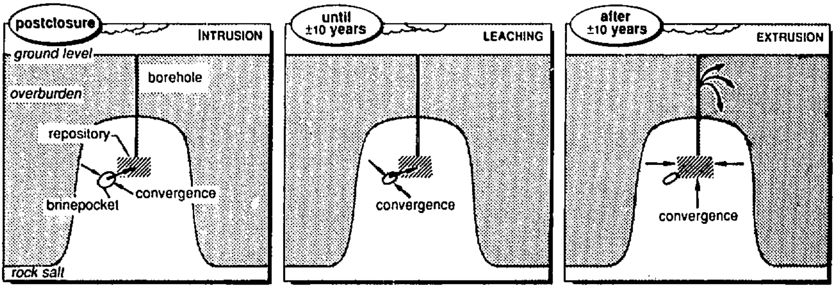

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Figure 13.7. Scenario F initiated by inadequate cementing of boreholes.

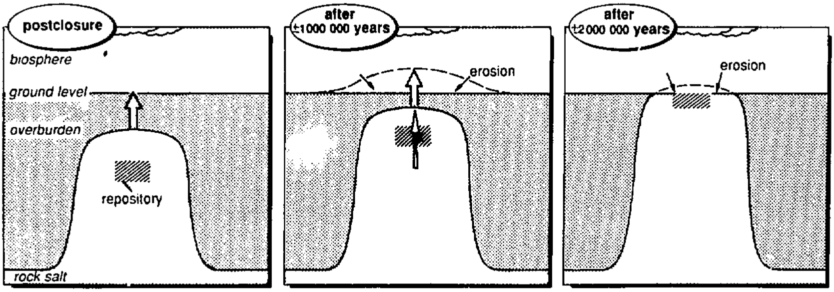

Figure 13.8. Scenario G initiated by diapirism to biosphere.

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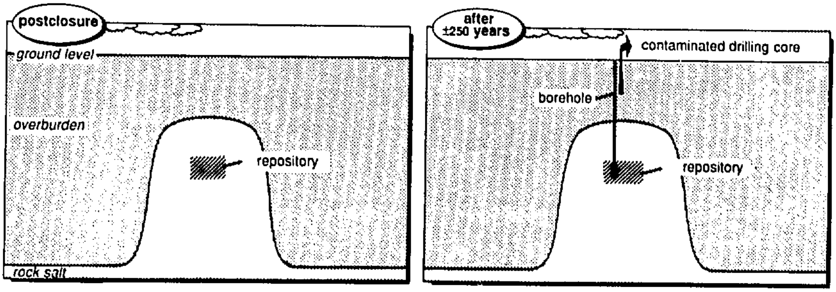

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Figure 13.9. Scenario H initiated by future exploratory drilling.

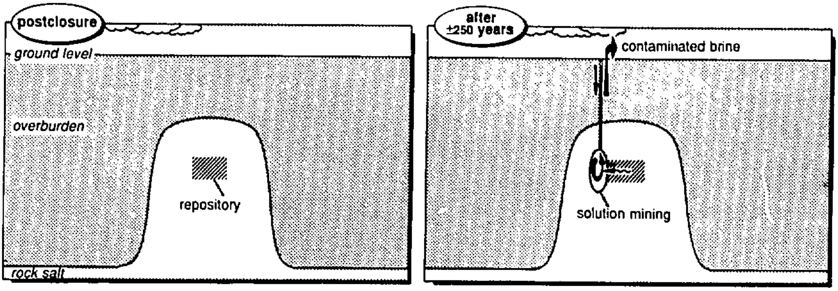

Figure 13.10. Scenario I initiated by future solution mining.

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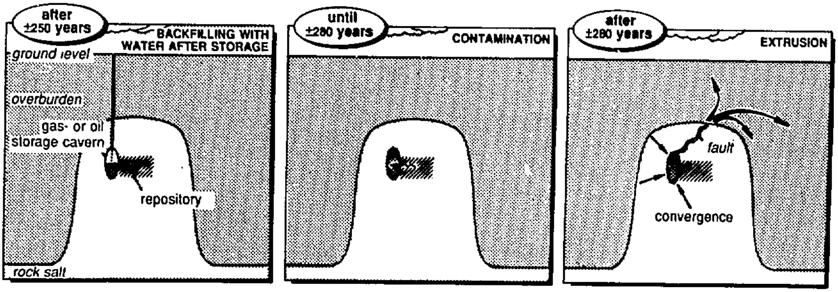

Figure 13.11. Scenario J initiated by leakage from future storage cavern.

XBL 906-2044

tion of salt particles from a brine solution that has returned to the surface after passing through a leached cavern containing a borehole with fission waste.

- Scenario J - initiated by leakage from future storage cavern. It is assumed that knowledge about the presence of the radioactive waste repository in the salt formation has been lost, and a solution cavern is being constructed in the salt to store oil or gas. It is further assumed that the new cavern communicates with a borehole containing waste from the lost repository, as shown in Figure 13.11. After the hydrocarbon storage ends, the cavern is flooded with water and then sealed. In the course of time, this water becomes contaminated and migrates from the salt formation through a fracture at the top of the cavern. The fracture is created when the hydraulic pressure exceeds the local rock stress, and exposure ultimately takes place following pollution of the groundwater and later the biosphere.
- Scenario K - initiated by future conventional mining. It is assumed that knowledge about the presence of the radioactive waste repository has been lost and that an underground mine is being constructed in the salt formation, as shown in Figure 13.12. Moreover, failure to detect the presence of the waste is also assumed. Exposure to radiation takes place when a mine gallery is constructed too close to an unknown repository hole containing fission waste.

With regard to the above mentioned scenarios centering around human activities (H, I, J, K), it should be noted that, in principle, these are not tied to particular periods. Proper management and inspection should make it possible to prevent the events described in these scenarios from occurring during the operational period, that is, prior to sealing the disposal facility.

13.4. Summary of Safety Study Results

The radiological effects to members of the human population were calculated for each of the scenarios. This was done on the assumption that the probability of occurrence for each scenario is 1. The results are in doses. No time restrictions were made; the process of analysis was continued until the dose diminished.

The results were: (1) that it was not possible to discriminate between the various formation types, and (2) that the human intervention scenarios lead to the highest doses. The probability for human intervention to occur is expected to be smaller in bedded than in dome or pillow salt. Furthermore, it is expected that a probabilistic approach in terms of health risk limits would not lead to unacceptable results.

13.5. Supporting Research

The following research was carried out to support the safety study:

13.5.1. Geology

An inventory of the geology and genesis of salt formations in northern and eastern Netherlands was made. This was a compilation from the open literature and involved areas in the northern and eastern Netherlands where the thickness of salt deposits exceeds 200 m. This produced 34 locations where a salt dome or pillow is present and four areas with bedded salt. The study focused not only on describing the present situation but also on the geological history and the tectonic stability of the salt. The report contains data on: depth, size, profiles including adjacent strata, genesis, and characterization of the salt formations considered. The expectation of encountering anhydrite layers in the salt formations is also given.

13.5.2. Geohydrology

Geohydrological and geochemical properties of some deep aquifers in northeastern Netherlands were studied. This yielded the data necessary for calculations on transport of radioactive materials through the geosphere. The data include such factors as: permeability, porosity, sorption characteristics, changes in groundwater levels, groundwater chemistry, groundwater age, etc.

The migration and geochemical aspects of plutonium, americium, neptunium and technetium in aquifers was investigated. Kd values for these four important radionuclides were determined for aqueous conditions in different types of sand, comparable with the arenaceous aquifers overlying the salt formations in The Netherlands.

A numerical code, called **METROPOL**, was developed that is able to correctly treat the high concentrations of salt expected to occur in the groundwaters near salt formations. The code is designed to handle transport, decay and adsorption of a large number of radionuclides.

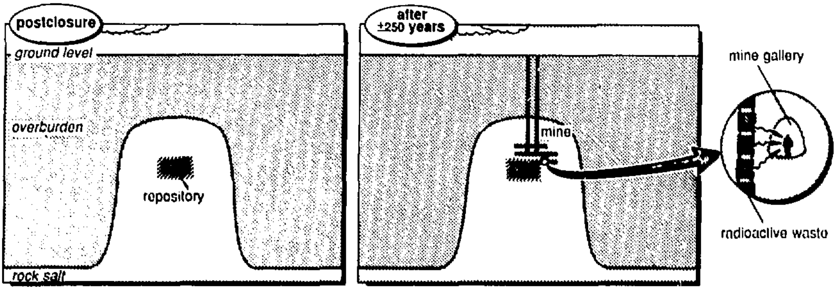

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Figure 13.12. Scenario K initiated by future conventional mining.

13.5.3. Rock Mechanics

The scenarios considered in the safety study were defined according to the principle that impermissible stresses and deformations will not occur, either during periods of construction and operation or after sealing and closure. This principle was supported by a number of calculations of temperatures, stresses and deformations for each disposal concept considered.

The long term rheological behavior and transport properties of dry and wet rock salt were investigated. This study aimed at the deformation behavior and formation of microfractures and their effects on the local permeability of salt. The purpose was to verify and improve, through appropriate constitutive equations, the basic relations describing the long-term deformation behavior of rock salt. The permeability of anhydrite and the deformation behavior of salt granulate were also investigated.

The consequences of inhomogeneities on the isolation capability of a salt formation were studied. In this work, the problem was to determine what inhomogeneities are to be expected in rock salt, according to their nature, size and location. Subsequently, it was determined whether their presence leads to different, possibly inadmissible conditions of stress and deformation.

13.5.4. Radiation Effects

The occurrence of changes in the crystal lattice of rock salt as a result of irradiation has been studied. These changes are evident, among other things, in the partial conversion of NaCl into sodium colloids (small droplets of sodium) and chlorine gas bubbles. This process is accompanied by the storage of energy in the system.

With regard to safety, it may be asked what quantities of energy can be stored in this fashion and in what volume of salt? How, under what conditions, and at what rate might this energy be released? Subsequently, as part of the safety study, a calculation was made of the maximum temperatures, stresses and deformations that could develop from the release of this stored energy resulting from radiation damage.

13.5.5. Mining Engineering

To carry out the safety study, a large number of data were required about the design, lay-out, operation and sealing of the disposal facilities. A report entitled, "Location-independent study concerning the construction, operation and sealing of potential facilities for the definitive disposal of radioactive waste in rock salt formations in The Netherlands," resulted in location-independent, pre-designs for the disposal concepts under consideration. These pre-designs were based on using the following mining techniques:

- Conventional mines with shafts and galleries, providing disposal space for all categories of radioactive waste, and
- Deep boreholes from the surface, suitable for the disposal of HLW, in combination with various types of caverns, suitable for disposal of LLW and MLW.

In addition, this study also investigated the question, in which of the rock salt formations (domes, pillows, bedded salt) are the various techniques to be regarded as feasible with the present levels of technology?

13.6. Summary of Results from Supporting Research

The results of the current earth sciences research program in The Netherlands can be summarized as follows:

13.6.1. Geology

A total of 38 salt formations have been identified, which includes:

- 19 salt domes
- 15 salt pillows
- 4 areas of bedded salt.

The geologic structure of the overburden for these salt formations is well known for the shallow rock strata of the Quaternary and part of the Tertiary. Less is known about the deeper strata in the Cretaceous, Jurassic and Triassic.

Depths to the top of the rock salt vary from approximately 170 m, for the shallowest dome, to approximately 2,200 m, for the deepest bedded salt sequence. The thickness of the rock salt also varies considerably, from several hundred to several thousand meters. The horizontal extent of salt domes at a depth of about 1,000 m is usually in the range of 10 to 20 km^2; and in one case, it is more. The internal structure of the individual salt formations is generally unknown. However, on the basis of regional geology, it is possible to state certain expectations with regard to the presence of inhomogeneities within the salt.

The external rate of uplift over the past 400,000 to 500,000 years for a number of salt formations is a maximum of 0.25 mm/y. Allowing for a subrosian rate of 0.15 mm/y means the effective uplift for the interior of the salt formation is at a maximum rate of 0.40 mm/y. This is an average over the time period and for a horizontal section through the salt formation.

The following options for the exploration of salt formations are available:

- methods from the earth's surface. These yield no more than an approximate survey of the depth to the top of the salt and the horizontal extent at this elevation.
- methods from boreholes drilled above and around the sides. These yield a good survey on the top side and flanks of the salt formation.
- methods from boreholes drilled into the salt. These yield a fair survey of the interior of the salt formation.

It is necessary to penetrate the salt formation to obtain a good survey of its internal structure; this is an indispensable step prior to developing a definitive design for the disposal facility.

13.6.2. Geohydrology

An inventory of geohydrological data in northern and eastern Netherlands made it possible to produce schematic profiles for the geohydrology of the strata overlying the 38 salt formations. In view of the limited amount and the generally regional character of available data, this inventory was done by means of a reservoir analysis method. The geohydrological profiles, together with supporting geological data, provide important input data for the safety study.

The **METROPOL** model was developed and used in the safety calculations to provide results for the rate of radionuclide transport through the subsurface. Checks on the reliability of this model began in 1985, and were performed in large part within the framework of the international **HYDROCOIN** study. The results for the situations investigated were positive and provide support for the further application of **METROPOL**. In a follow-up project, known as **INTRAVAL**, the reliability of the model will be tested further as an essential part of this ongoing study.

Data on the mobility of radionuclides through the subsurface were obtained from the following sources: an NEA data bank, research in the Federal Republic of Germany, and laboratory experiments. The application of these data in the safety study was always performed using the principle of the upper limit.

13.6.3. Mechanical Behavior of Rock Salt

In the course of the present research, the system of constitutive equations for the mechanical behavior of rock salt was further developed, assessed and found to be reliable for practical applications. The theoretical basis for the correlations between the mechanical behavior of rock salt as measured in the laboratory and as measured *in-situ* is not yet optimal. Further study on this problem is desirable in a subsequent phase.

A material has been developed and tested for the backfilling and sealing of boreholes, galleries, chambers and shafts. It consists primarily of salt granulate of a suitable composition that has been carefully dosed with a measured quantity of water. The composition of this material has been optimized with regard to its recrystallization properties. Over time, this material fuses solidly with the surrounding salt.

The stress conditions under which microfractures form in salt have been determined, as well as their effect on the long-term mechanical behavior of salt. Inhomogeneities in the salt, which are more readily deformable than the salt itself, are not expected to have any adverse effect on the isolation capability of the salt formation. Inhomogeneities that are stiffer and more brittle than salt (for example, anhydrite) may fracture under the prevailing stress and temperature conditions, if larger-sized elongate masses of such material are located in the immediate vicinity of the repository. The extent to which this would erode the isolation capability of the salt formation will have to be established by further study.

13.6.4. Mining Engineering

The construction and operation of a disposal facility for radioactive waste in salt formations in The Netherlands is technically feasible, except for a dry cavern in bedded salt at great depth. This conclusion is based on the predesign study of disposal concepts.

From the standpoint of mining engineering, this conclusion is further supported by:

- extensive experience in conventional mining of salt,
- the *in-situ* projects in the Asse II salt mine in the Federal Republic of Germany, and
- research projects carried out elsewhere in the world. Corresponding experience and supporting information obtained experimentally are lacking for the deep borehole technique. On the other hand, the necessary experience for the cavern technique is available in mining engineering.

Sealing of the disposal facility using the mining technique can be installed in a manner that can be controlled and inspected. This is not readily possible with the current technology that is available for caverns and deep boreholes.

On the basis of present technology, Dutch salt formations that are not deeper than about 1,800 m are accessible for geologic disposal of radioactive waste. This means that the 38 salt formations that have been identified can be grouped according to current technology for the various disposal techniques as follows:

- 17 lie within the depth range of underground mines,
- 14 lie within the depth range of deep boreholes and dry caverns, and
- 26 lie within the depth range of deep boreholes and brine-filled caverns.

The size of all these salt formations is sufficient for disposal purposes. In the development of techniques for radioactive waste disposal, the mining method has a substantial lead over the technique of drilling boreholes from the surface.

In general, earthquakes cause little or no damage underground. The probability of a strong earthquake in northeastern Netherlands is estimated to be certainly less than one in a million years; the trigger mechanism for such an event is very probably absent. The possible radiation hygiene consequences from an earthquake that causes a disposal facility to flood are comparable to those of Scenario D.

13.7. Overall Conclusions

13.7.1. General Conclusions

- The construction and operation of a disposal facility in Dutch rock salt formations is, in principle, technically feasible. Two essentially different methods of mining are available: (1) conventional mine construction, and (2) deep boreholes drilled from the surface in combination with caverns.
- The program has been assessed on the basis of foreign safety criteria, international recommendations, and the risk limits proposed in the Dutch Indicative Multi-Year Program for Environmental Management. The results of the investigations justify the expectation that safe disposal of radioactive waste in rock salt formations, of the nature and size as very probably occur in the subsurface, is possible.
- On the basis of these two conclusions, the continuation of investigations into the possibilities of radioactive waste disposal in Dutch rock salt formations should be regarded as justified from the safety engineering viewpoint.

13.7.2. Conclusions on Continuation of Research Program

- On the basis of the safety criteria described above, the results of the safety and mining engineering studies provide no reason to exclude any particular disposal concept or formation type from further investigation.

- According to the safety study, a disposal mine provides better isolation of the high-level and fission waste than does disposal in deep boreholes. With regard to the isolation of low-level and medium-level waste, no great differences emerged from the disposal concepts that were considered.
- By comparison with other techniques, research and development on the technology of radioactive waste disposal is concentrated worldwide on the mining technique. Accordingly, this technique is in a more advanced state than the borehole method.
- On the basis of the above two conclusions, it appears logical at this time to concentrate any further research effort on the mining technique. If deep borehole disposal should appear promising in the future as a result of technological advances, the choice of mining can be reviewed.

Future geological research in The Netherlands will be directed at improving our understanding of such processes as: diapirism, subrosian and the effects of an ice age and permafrost on subrosion, the formation of subglacial depressions, and the general factors affecting ice ages. There is still not enough quantitative treatment in these subjects. As a better understanding develops, the results can be used as input in site-specific safety analyses. By doing so, we would create a proper basis for site selection which we feel we still do not have.

Chapter 14

Radioactive Waste Management in Spain Main Activities up to the Year 2000

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14.1. Abstract

This abstract describes the present status of the main activities developed by the Empresa Nacional de Residuos Radiactivos, S. A. (ENRESA), the Spanish national organization responsible for the management and disposal of radioactive wastes, following the usual classification of low and intermediate activity and high level and long lived waste.

Special emphasis is given to the site selection and characterization work which proceeds according to the flow diagram for HLW shown in Figure 14.1.

The paper discusses also the characterization activities developed at the "El Cabril" site, which has been proposed as a disposal site for low and intermediate level waste produced in Spain up to the year 2000.

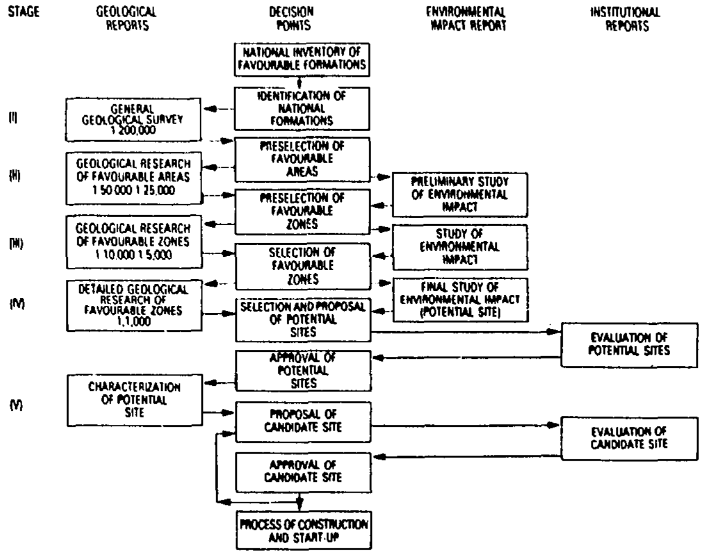

Figure 14.1. Flow diagram of site selection plan currently projected for the final disposal of high level waste.

Editors Note

This is the abstract that was submitted prior to the Workshop.

Chapter 15

Swedish Program for Disposal of Radioactive Waste - Site Characterization for a High-Level Waste Repository

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15.1. Summary

The safe and efficient management of radioactive waste from nuclear power production in Sweden is the responsibility of the owners of the nuclear reactors. This responsibility also includes the financing of all costs. To fulfill their obligations, the four utilities that operate nuclear power reactors have commissioned the Swedish Nuclear Fuel and Waste Management Company (SKB) to carry out the necessary work.

SKB has developed a waste management system that will ensure a very high level of safety for a long time into the future. Plants and facilities for the transportation of waste, temporary storage of spent fuel, and final storage of short-lived, low- and medium-level waste have been constructed and are in operation. The system now in place will ensure safe handling of all radioactive waste in the country.

A central interim storage facility for spent fuel, CLAB, was put in operation in July 1985. A sea transport system for spent fuel and other kinds of radioactive waste has been in operation since 1982. A final repository for short-lived, low- and intermediate-level waste was put in operation in April 1988.

The remaining problems on which decisions have not been taken are a conditioning and encapsulation plant for spent fuel and a final repository for long-lived waste. The feasibility of final disposal of spent fuel in Sweden has, however, already been demonstrated.

In 1986, SKB presented a program for research, development and other measures. One important goal of the continued R&D work is to improve knowledge in order to provide a better basis for optimizing the final method of disposal and permit greater flexibility in the choice of a repository site. It is envisaged that selection of a disposal concept will be made in the mid 1990's. The ongoing work is to a great extent being devoted to development, testing and verification of the techniques, methods and models to be used in the site characterization program. With respect to specific locations, several potential sites have been thoroughly investigated and analyzed during the last decade. It was concluded in the KBS-3 feasibility study (SKBF/KBS, 1983) that there are several sites in Sweden that can provide suitable conditions for the construction of a safe final repository.

The milestones for locating the final repository site are in essence:

- selection and acceptance of two possible candidates as potential repository sites before the mid 1990's,
- detailed characterization of both sites using tunnels/shafts by the end of the 1990's, and
- preparation of a preliminary safety report by the turn of the century providing the basis for a license to locate a repository at one of the sites.

During the period 2000-2010, the safety report will also be substantiated by technological developments and field demonstrations using pilot and long-term, *in-situ* tests. The planning goal is that all necessary permits to start construction of the encapsulation plant and repository should be obtained around the year 2010.

Examples of SKB research projects of particular importance to site characterization are discussed. The need for conceptual models on different scales is recognized. The rationale for one of the major projects currently in progress,

The Hard Rock Laboratory (HRL), is presented. The scope of work during pre-investigations, construction and operation is outlined. Pre-investigations for the HRL commenced in the autumn of 1986 and will be finished in 1990. Throughout the construction phase, extensive data collection will be carried out to check and update the predictions made on the basis of the pre-investigations. The HRL is to be made available for experiments at depths of 400 to 500 m in 1993. It will then replace the current underground facility at Stripa as the main site for *in-situ* and demonstration experiments.

15.2. Introduction

Production of electricity in Sweden is based mainly on nuclear and hydropower plants. The nuclear power program consists of twelve reactors located at four different sites. The first reactor went into operation in 1972 and the twelfth, in 1985. The Swedish parliament has decided that all twelve units should be decommissioned not later than the year 2010 and that no new units will be constructed. This decision forms the basis for planning the Swedish waste management program.

The annual consumption of electricity gives rise to about 250 metric tons of spent nuclear fuel per year. By the year 2010, the accumulated amount will be some 7,800 metric tons. According to Swedish law, the owners of nuclear reactors are responsible for the safe handling and disposal of all radioactive wastes produced. In order to meet these requirements, the four utilities that own the power plants have formed the Swedish Nuclear Fuel and Waste Management Company (SKB).

SKB has developed a complete system for the safe management of radioactive waste in Sweden. Major parts of the system are already in operation. This paper describes the management of spent nuclear fuel, including research and development with emphasis on site characterization. The main objective of the Research and Development Program is that the final disposal site for spent fuel shall be approved and ready to start operation around the year 2010.

15.3. Nuclear Waste Management in Sweden

Sweden is in a good position with respect to waste management of spent nuclear fuel, reactor operating wastes and decommissioning wastes. An overview of the waste system is outlined in Figure 15.1.

15.3.1. Reactor and Decommissioning Wastes

A final repository for low-level waste (LLW) and medium-level waste (MLW) has been in operation since April 1988. The repository, SFR, has been built at the site of the Forsmark nuclear power station. It is located in bedrock under the sea about one kilometer off the Forsmark shore. The repository is covered by fifty meters of hard rock, a few meters of sediments, and about five meters of sea water. The location below sea level is advantageous because the driving forces for groundwater flow are low. The drilling of any fresh water wells into the repository must naturally be delayed for several hundred years.

The facility consists of rock caverns of various designs, depending on the type of waste to be emplaced. The intermediate-level waste, which contains most of the activity, will be deposited in a silo-like concrete structure cast inside a cylindrical rock cavern. The waste will be isolated from the surrounding rock by concrete walls and a layer of bentonite between the silo and the rock. The design of the repository will insure that close to 100 percent of the radioactive materials will be contained until they have decayed and no longer constitute a hazard to human beings or the environment. SFR will accommodate all the 90,000 m^3 of LLW and MLW expected to be generated in Sweden up to the year 2010. The present facility has a capacity of 60,000 m^3; an expansion is planned for the end of the 1990's.

15.3.2. Spent Fuel

The basic policy for the management of spent fuel from Swedish nuclear power plants has been established in a few firm guidelines:

- all radioactive waste including spent fuel will be taken care of within Sweden,
- no reprocessing of the spent fuel will be done,
- before final disposal, the fuel will be kept in an interim storage facility for about 40 years,
- the system for handling the fuel shall be designed to meet the requirements for safeguarding special nuclear materials, and
- a system for final disposal of spent fuel should be worked out by the present generation of man that is now using the electricity from nuclear energy.

The decision on the method to be used for final disposal should be made around the year 2000 and be based on a broad scientific understanding of the problem.

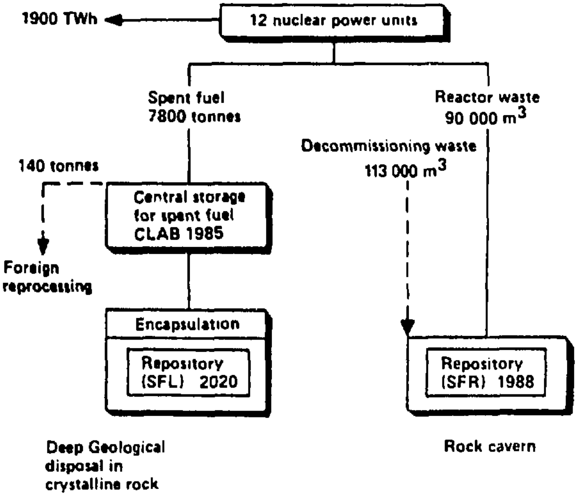

Figure 15.1. The Swedish Waste Management Scheme based on projected generation of waste up to the year 2010.

15.3.3. Interim Storage

The spent fuel will be stored for about 40 years in the central interim storage facility, CLAB, which is located close to the Oskarshamn nuclear power plant. This interim period allows the residual heat and radioactivity to decay by a factor of about ten, thereby making the handling and final disposal considerably easier.

CLAB was constructed in the early 1980's and put in operation in 1985. It consists of a ground level receiving and handling building and an underground complex in rock. The spent fuel is handled and stored under water. The capacity is now about 3,000 metric tons of spent fuel in four storage pools. An expansion is planned for the mid-1990's so that it will be possible to store all fuel from the Swedish nuclear program. There are different options for this expansion, e.g. a closer packing of fuel in existing pools by different means or the construction of additional pools. The various options are now being evaluated.

CLAB can easily receive about 300 metric tons of spent fuel per year. At present, about 250 metric tons arrive each year and about 1,000 metric tons are now in storage. Core components and reactor internals can also be stored at CLAB.

15.3.4. Transportation of Spent Fuel

All present major nuclear facilities in Sweden are located along the coast. This makes it natural to use sea transportation for all heavy transport to and from these plants. Thus, a sea transportation system has been built up and is in use for the shipment of spent fuel as well as other radioactive wastes. The M/S Sigyn was put in service in 1982, and has since transported more than 900 metric tons of spent fuel and some 3,000 m^3 of MLW. The spent fuel casks meet the stringent IAEA requirements on radiation shielding and the ability to withstand external stresses and fire.

15.3.5. Final Disposal of Spent Fuel

According to Swedish law, before the government issues an operating permit, the owner of a nuclear power plant must show how and where the spent fuel produced by plant operations can finally be disposed of in a way that is acceptable for safety and radiation requirements. This requirement was instituted by parliament in 1977, and was applied to the last six reactors in the program. In order to meet the requirements of the law, SKB instituted an extensive research and development program. This program was the basis for the KBS-3 report describing one feasible method of meeting governmental requirements (SKBF/KBS, 1983). The report was published in 1983 and approved by the Swedish government in 1984, after an extensive review by both domestic and foreign experts (Ministry of Industry, 1984).

Sweden has not set specific criteria for the level of safety that must be attained in the design of a final repository. The overall construction objective for nuclear facilities, however, is that they shall be designed so as not to result in higher individual doses of radiation to human beings than that from the surrounding environment. This means less than 0.1 mSV/year. This general objective permits a high degree of flexibility in research, design and optimization of the final repository. Swedish authorities have expressed the intention that future generations shall have at least the same degree of protection as the present population.

As already mentioned, the law also makes the owner of nuclear plants responsible for the research and development work needed in the safe handling and disposal of waste. The law also states that the research program must be comprehensive and that alternative methods of disposal shall be evaluated. The research program must be submitted to the pertinent authorities for review every three years, starting from 1986 (SKB, 1986). The second program is to be submitted in September 1989. It will provide a detailed plan for the coming six years and an outline of all research, development and other measures that will be needed thereafter.

Inasmuch as the existing waste management system is complete in terms of the way in which waste is to be handled and stored in a safe manner for a long time into the future, the R&D program is mainly directed toward final disposal of spent fuel.

The important general goals for the present research program are to:

- evaluate alternative concepts to KBS-3,
- improve the knowledge and data base on engineered barriers and bedrock properties in order to optimize the engineered and natural barriers at a specific site,
- study and evaluate possible sites in order to design a safe repository on an acceptable site, and
- improve and further develop the methodology for safety assessment in order to increase the understanding of safety margins and, thus, contribute to increased acceptance of the final disposal concept.

Specific research goals are to:

- select a principal concept for the spent fuel repository and start detailed characterization of at least two sites in the mid-1990's,
- submit a license application for approval of a specific site in the first years of the next century, and
- start construction of a repository in the year 2010 and an encapsulation plant in due time for the start of disposal operations in the year 2020.

15.4. Site Characterization for Spent Fuel

15.4.1. Essential Rock Properties

The geological formation itself is a prerequisite for a safe repository for spent fuel. The implications from the geology provide a reliability and, hence, a sufficient predictability to cope with the time spans involved.

The properties of the rock that are essential to achieve a safe final repository are somewhat dependent on the choice of the engineered barrier. The Swedish approach to repository design is aimed at total isolation of the waste to be provided by an appropriate combination of engineered and natural barriers. This philosophy was adopted both in the KBS studies and in the design of the SFR facility. By choosing long-duration engineered barriers, the role of the rock mass is to provide prevailing conditions with respect to groundwater flow, groundwater chemistry and mechanical protection. The basic (probable) scenario thus provides that the canisters will not fail during the time span that the spent fuel is a potential hazard to the environment. A secondary scenario is to evaluate individual doses as a result of early canister failure.

It is envisaged that the current Swedish approach to repository design, i.e. canisters with a very long service life, will be accepted and implemented. The general principles that provide a basis for *proof of concept* are:

- choice of materials for the engineered barriers that, according to geological evidence, will prevail in a typical repository environment, and
- combination of barriers such that their interaction in the repository can be analyzed

using scientific theories that are widely accepted.

The KBS-3 method, as mentioned above, is a multi-barrier concept. The general outline is for a repository depth of 500 m. The canisters, 1.5 m in diameter, will be placed in holes that are 7.5 m deep spaced 6 m apart. Some 35 km of drifts will be needed spread over an area of about 1 km^2. The fuel will be encapsulated in copper canisters with a wall thickness of 10 cm, and the deposition holes will be backfilled with highly compacted bentonite. The drifts and tunnels will be backfilled with a mixture of sand and bentonite.

The safety analysis for the KBS-3 method was a feasibility study that incorporated several conservative simplifications. Even in this analysis some essential general properties of the rock were identified. Based on these analyses, it was concluded that, with respect to safety, several sites investigated in Sweden were suitable for a final repository.

The analyses provide a general basis for identifying the properties of the rock that are essential for the isolation of radioactive waste. It does not, however, give a detailed account how variations in processes or parameters affect the overall safety of the concept. Such a study is now in progress. The study, SKB-91, will be based on the KBS-3 concept and utilize data from the Finnsjön study-site. SKB-91 will specifically investigate how variations in properties and data in both the near field and far field affect isolation, the rate of dissolution, and transport of solutes; in other words, how robust is the disposal method with respect to these parameters. It is planned for the study to provide a basis for sensitivity studies of future possible sites so that an early evaluation of the safety can be achieved. This work will also provide a focus on the models and parameters that are of prime importance for site characterization and a test on how models should be validated and applied.

15.4.2. Strategy for Site Characterization

Site characterization is intended to provide the data needed for repository design and safety analyses. The work includes data acquisition, construction of conceptual models, predictive analyses using numerical models, and evaluation of the predictions (validation).

The work of site characterization is focussed on:

- description of *tectonics*, e.g. localization of potential zones of movement,
- description of *groundwater flow*, e.g. localization of flow paths, identification of discharge areas, and distribution of groundwater flux, and
- *groundwater chemistry*, e.g. compositions of groundwater in fracture zones and stagnant water in the rock matrix, data to support groundwater modelling, and data for analyses of engineered barriers and fixation of nuclides in the rock.

The characterization is done in stages. It is important to recognize that the conceptual models become more detailed in the course of *pre-investigations*, detailed characterization, and repository construction. The refinement of the models also provides an opportunity to improve the design of the repository. The first step may be to define the volume of the repository, next to locate the repository tunnels, and finally to select exact positions for emplacement of waste. With respect to performance assessment, it will also be possible to make more detailed evaluations of the near and far fields as the conceptual models become more detailed.

The aim of the current Swedish program is to have a few potential sites in 1992. These sites should be such that a license application for any one could be submitted around the turn of the century. The earlier KBS-3 study established that several sites exist that from a safety point of view are acceptable. The sites to be selected in 1992 must also be acceptable from the standpoints of transportation, infrastructure and socio-economic factors.

In order to make an early evaluation of safety, design and other environmental effects, pre-investigations will be conducted on each site. These investigations are to demonstrate that the groundwater flow on the sites is low, that the chemical environment within the rock is advantageous, and that mechanical stability can be achieved during repository construction. The pre-investigations will provide a general characterization of the site based on a few deep core holes. This work will determine potential repository volumes, and provide guidelines for the later detailed characterization of the repository as well as the rocks between it and the discharge areas. Sites situated offshore beneath the Baltic Sea cannot be excluded.

Two sites will be *characterized in detail* before the turn of the century. This will include access to the proposed repository level. These detailed investigations will confirm that a suitable rock volume for the repository exists and provide data for the detailed design work and optimization of the engineered barriers. It must also provide site-specific data for a license application.

Present analyses show convincingly that the near field is the most important rock volume from the standpoint of safety. *Characterization during construction* will provide the data needed to make a detailed description of the near field and to emplace the spent fuel in the repository.

15.4.3. Research and Development for Site Characterization

Data from the investigations are analyzed and presented in conceptual models that are needed for the design and calculation of, for example, groundwater flows. It is believed that a single model will not be sufficient for both global and detailed investigations. A practical approach is to set up the conceptual models on different geometrical scales. For example, appropriate scales for the work in Sweden are:

- *regional scale*: >> 1 km, relevant for regional groundwater flow and for general tectonic description;
- *site scale*: 100-1,000 m, relevant for definition of repository volumes and far field characterization;
- *block scale*: 10-100 m, relevant for characterization of the near field to the canisters; and
- *box scale*: 0-10 m, relevant for characterization of the very near field surrounding the canisters, i.e. the so called disturbed zone where changes in flow within the rock are very close to an opening.

It is possible to set up conceptual models on every scale and explain how the data is interpolated and extrapolated. It is also possible to set up numerical models that are consistent with the data. As shown on Figure 15.2, the following issues should be evaluated for each scale:

- the conceptual model
- groundwater flow
- groundwater chemistry
- transport of solutes
- mechanical stability.

The evaluation should include the basis for validation. It is recognized that validation will not be possible for all issues on all scales.

SKB is carrying out several major projects to enhance an understanding of these issues. The Hard Rock Laboratory, described in the next section, includes all the above issues. The third phase of the international OECD/NEA Stripa Project is focussed on groundwater flow and transport of solutes on the block and box scales. The Fracture Zone project at Finnsjön is directed at an investigation of groundwater flow and solute transport on the site scale. The chemistry and transport of solutes are being studied in natural analogues at Poços de Caldas. A study at Lansjärv on post-glacial faulting is directed at mechanical stability and groundwater flow and chemistry on the site scale. The SKB-91 study will use existing data from the Finnsjön study-site to evaluate the issues and apply them to a complete analysis of safety. More detailed descriptions of these projects are contained in the SKB Annual Reports. Table 15.1 presents an overview of projects and scientific issues for the different scales.

The main relevant uncertainty in site characterization lies in the issue of solute transport. At present there is no single accepted theory that describes the transport of solutes in crystalline rocks. The uncertainty lies mainly in the problem of describing the groundwater flow paths in the rock. Few experiments provide a physical description of these flow paths. Investigations of this transport problem have mostly been based on an analysis of data using existing models that were not developed for flow in fractured crystalline rock. Whether these studies discriminate between the models is a matter of opinion.

One recently devised method of actually describing the physical flow paths is by simply mapping the inflow into a tunnel. Such work has been performed at Stripa, SFR and a few full-face bored tunnels in Sweden. It can be argued whether these observations are relevant or not to the actual flows in the rock. SKB has therefore used more sophisticated techniques to explore the matter further. A geophysical down-hole method using a radar technique has been used in conjunction with the injection of saline tracers in fracture zones. The radar maps the distribution of this saline tracer. The results are still being evaluated, but the technique shows promise in describing actual flow paths in rock.

The *channelling concept* was utilized in the safety analysis of the SFR facility. It is the most conservative approach and was used in a model exercise that, as yet, cannot be excluded. The question of flow path characteristics will, however, not be a critical factor in the performance assessment of a repository if the design is aimed at total isolation of the waste within the engineered barriers. It has been convincingly demonstrated that the use of highly compacted bentonite as a buffer will mean that the migration of corrosive fluids to the canister and transport of

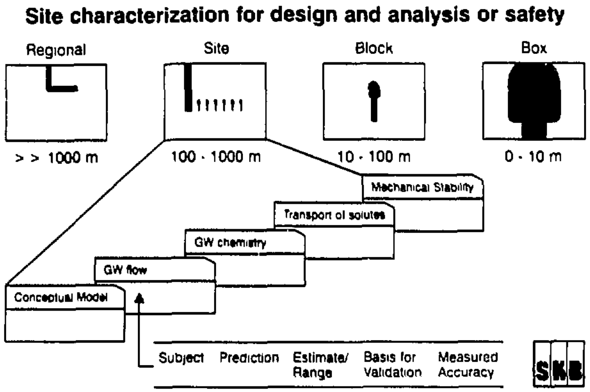

Figure 15.2. Site characterization. Issues and scales.

Table 15.1. Overview of projects and scientific issues to different scale

Issue	Scale			
	Regional	Site	Block	Box
Conceptual model	HRL - - - Lansjärv SKB-91	HRL - Finnsjön P de C Lansjärv SKB-91	HRL Stripa - P de C - SKB-91	HRL Stripa - P de C - SKB-91
Groundwater flow	HRL - - - SKB-91	HRL - Finnsjön Lansjärv SKB-91	HRL Stripa - - SKB-91	HRL Stripa - - SKB-91
Groundwater chemistry	HRL - - - -	HRL Finnsjön P de C Lansjärv SKB-91	HRL - P de C - SKB-91	HRL - P de C - SKB-91
Transport of solutes	- - - - -	HRL - Finnsjön P de C SKB-91	HRL Stripa - P de C SKB-91	HRL Stripa - P de C SKB-91
Mechanical stability	HRL Lansjärv SKB-91	HRL Lansjärv SKB-91	HRL - SKB-91	HRL - SKB-91

nuclides from the spent fuel to the near field are governed by diffusion.

Even if analyses do not take the various flow paths into account, they are still of greatest importance to repository design. The design objective is to avoid positioning canisters close to highly conductive zones. The precise geometry of conductive fractures close to canisters can be determined in the course of the repository construction.

15.5. Critical Importance of Hard Rock Laboratory

15.5.1. Objectives

The Hard Rock Laboratory is an important step in the design and development of a safe final repository for spent fuel in Sweden. Whereas the research activities in the Stripa underground laboratory will be completed in the early 1990's, it has been deemed of high priority to build an underground research laboratory where investigations can be continued at a high scientific level to broaden the available body of knowledge. The main objectives of the laboratory are to:

- test and verify methods of site characterization,
- refine and test the methodology of adaptive design and construction of a repository, and
- collect data of significance for the safety of a repository and the analysis of that safety.

The objectives of the Hard Rock Laboratory have been set so as to tie in with the overall objectives of the SKB program. It is thus important to:

- verify that pre-investigation methods used for characterizing the rock provide data that are pertinent to safety,
- develop and verify the efficacy of the methods used in detailed characterization before 1995, when they will be applied to the proposed sites,
- refine and, in a large rock mass at the actual repository level, test the methods and models for groundwater flow that are essential in optimizing the repository system and in providing the safety analysis required around the turn of the century for the site license,
- provide access to a significant mass of rock in order to develop and refine high standards of design, construction and operation of a repository before start of construction around 2010, and
- test, investigate and demonstrate the adequacy of components in the repository system that are significant for the long-term behavior of the final repository at full scale, under representative conditions and at actual repository depth. Tests will be performed to the extent necessary, with respect to time and geometric scale, to provide basic data for the required permits to be issued for construction to start around the year 2010.

Work on this project started near the end of 1986. The activities can be grouped in three separate phases: pre-investigations, construction and operations. It is planned for construction to start in 1990, and operation of the laboratory will be able to commence in 1994. Investigations and research will be performed in all phases.

15.5.2. Pre-Investigations

The aim of the current phase of pre-investigations is to site the laboratory, set up conceptual models on different scales that characterize natural conditions in the bedrock, and predict the changes that will occur during construction of the laboratory. In view of existing services and other infrastructure, it has been proposed that a location at CLAB (Oskarshamn) or in the vicinity be investigated. Evaluations of the regional setting and characterizations of the target area have been presented by Gustafsson et al. (1988, 1989).

15.5.3. Construction

The second phase of construction is planned to start in the autumn of 1990. An access tunnel will be blasted down to a depth of about 500 m below ground level (see Figure 15.3). Predictions from the pre-investigation phase will be checked and discrepancies explained.

The construction work will proceed in two steps. The first will include tunnelling to a depth of 350 m, and the second will proceed after a delay of six months to permit an updating of the characterization of the lower levels. The second step will complete the tunnelling to 500 m and the excavation of parts of an experimental area (Figure 15.3). It is expected that approvals from pertinent authorities for construction of the laboratory will be obtained during 1989. Predictions developed during the pre-investigation phase will be checked throughout the process of construction.

15.5.4. Operation

The third phase of operations is planned to start in 1994 and may last several decades. The

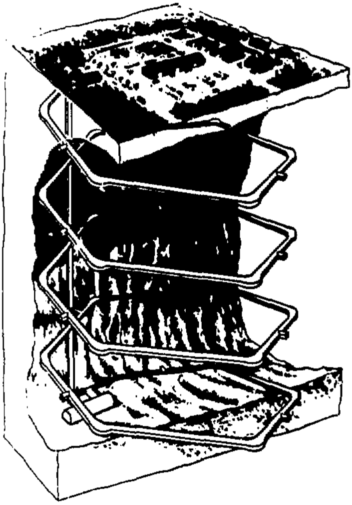

Figure 15.3. Outline of the design for the Hard Rock Laboratory.

experimental program for this phase is now in the planning stage. An outline of the projected program is directed toward the following activities:

- site scale tracer tests,
- block scale tracer tests,
- nuclide migration,
- block scale redox tests,
- methods for repository development, and
- interactions between natural and engineered barriers.

The *site scale tracer tests* will be focussed on transport in the far field and will be executed to support the later application for a license for the final repository site. The *block scale tracer tests* will focus on the problem of characterizing the near field. A canister configuration in rock of low hydraulic conductivity and with a certain distance to a major flow conduit will be simulated. These tests will also support the license application for the repository site.

The work on *nuclide migration* will involve a series of tests to investigate dissolution and migration of nuclides *in-situ*. Data and models for the chemical properties of radionuclides are to a large extent based on laboratory experiments. However, it is difficult to duplicate natural reducing conditions, the natural colloid content and undisturbed rock with fractures under relevant stresses in a conventional laboratory. These disadvantages can be avoided by *in-situ* testing, and the experiments will also support the license application.

The *redox tests* will be performed on the block scale to determine that a sufficient redox capacity is available along the flow paths. Reducing conditions are a prerequisite for a long service life of the copper canister. These tests will also increase our knowledge of the kinetics of reactions between groundwater and the fracture minerals.

Detailed planning on *methods for repository development* and *interactions between natural and engineered barriers* will start when the Swedish concept for the final repository has been approved around 1995. Work on methods of repository development will demonstrate how characterization of the near field is to be performed during construction of the repository. Interactions between natural and engineered barriers will be investigated in a pilot test at the site selected for the repository.

15.6. Concluding Remarks

Spent nuclear fuel and radioactive wastes of different types are generated in the operation of a nuclear power plant. These wastes exist and will exist irrespective of the future for nuclear power in Sweden. The wastes produced thus far and those still to be produced are a potential hazard if they are not properly managed. Sweden has access to a system of nuclear waste management that will ensure a very high level of safety for a long time. SKB has further demonstrated that it is possible to construct a safe final repository in Sweden for long-lived waste using present technology that meets very high standards with respect to safety and radiation protection. SKB has also developed a program for research, development and other measures that are needed in order to achieve an optimized system of waste disposal on a site in Sweden. This program is comprehensive and is being implemented with strong support from national and international experts.

From an international perspective, Sweden is in a good position with respect to nuclear waste management. The extensive international cooperation that SKB maintains in this field will continue to be a cornerstone of the Swedish program. This is important from the obvious benefits of the technical solutions as well as from the standpoint of a greater public understanding and acceptance.

The research on site characterization is focussed on problems that are important in perfecting a true understanding and description of the performance of a final repository.

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Chapter 16

Swiss HLW Programme: Status and Key Issues

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16.1. Abstract

In Switzerland the nuclear programme is small by absolute standards; 5 plants generating 3,000 MWe total are in operation and recent political developments imply that no new capacity will be on-line before 2000. However, the relative contribution to electricity production is high (21.5×10^9 kWh or 40 % in 1988), the plants themselves are of diverse kinds and from different suppliers (and hence have differing waste streams). The country is densely populated, the geology is complex and varied and the standards for environmental planning are very high. These facts lead to a situation in which radioactive waste disposal issues have a high socio-political and technical importance.

All types of radioactive wastes arising in Switzerland have to be taken into account in the planning of the national waste disposal organization, Nagra. Because the chosen fuel cycle strategy of the utilities involves reprocessing of spent fuel at foreign facilities, with possible return of wastes from COGEMA in France and BNFL in Britain, further waste types must be included in the planning inventory. These include vitrified high-level wastes and also various actinide-containing wastes solidified in cement or bitumen matrices. A subsidiary option for high-level wastes is direct disposal of conditioned spent fuel elements, but comparatively little work has been done on this approach. Further wastes to be disposed of include all reactor operational wastes, wastes from industry, medicine and research and wastes from decommissioning of all nuclear facilities in the country.

In this paper, the emphasis is on high-level waste (HLW), i.e. on reprocessing residues solidified in borosilicate glass. For such wastes, heat generation is important. Cooling will take place during pond storage before reprocessing, at the reprocessors facility and lastly at a Swiss intermediate storage facility based on dry cask storage. A total delay of 40 years between fuel unloading and final waste disposal is planned.

The paper is structured to present a summary of the current HLW project status followed by some observations on key geological issues. These "geological problems in waste disposal" are based upon experience gained in Swiss projects, but they are of general applicability.

16.2. Swiss HLW Programme

16.2.1. Repository Programme

After original studies of various rock types, at the end of the seventies attention was focussed upon clay formations (Opalinus clay) and upon the crystalline basement underlying northern Switzerland. For both these options, preliminary safety and design studies were performed. For specific field work, an investigation area (1200 km^2) was selected for first regional studies. In this area, sediments of increasing thickness cover the basement. The geology was directly investigated by drilling a series of holes each planned to traverse hundreds of meters of sedimentary layers and penetrate 1,000 m into the crystalline rock and by extensive vibroseismic measurements.

Detailed engineering and safety studies based on a mined repository concept at a depth of ≈1,200 m in the crystalline basement were performed within the scope of a major feasibility project. Following completion and review of this project, it was agreed to again widen the potential host rock options for further studies and that specific evaluations should be made of promising sedimentary formations. A first phase of this sediment programme was completed and documented at the end of 1988.

Based on analysis of existing geological data, seven sedimentary formations were evaluated and two of these selected for more detailed study. The two sedimentary options are

Opalinus clay and freshwater molasse. The former occurs in a laterally-extended, apparently homogeneous layer of limited thickness (≈100 m). The relatively heterogeneous freshwater molasse can have thicknesses up to thousands of meters. For both options, the reference repository depth is 800 to 900 m.

For all host rock options, the repository design concepts are similar. Vertical shafts access horizontal tunnel arrays in which the HLW packages are centrally emplaced surrounded by low-permeability backfill (compacted bentonite). Tunnel dimensions vary according to the mechanical and thermal properties of the rock; a design criteria is that most of the backfill and all of the host rock should not be exposed to temperatures above 100° C.

It is conceivable that long-lived intermediate-level wastes might also be stored with the high-level wastes. In hard rocks, emplacement would then be in silo structures spatially separated from the HLW. The criteria for allocation of long-lived wastes to a HLW repository or to a nearer-surface, horizontally-accessed LLW repository are dependent on the specific characteristics of sites to be chosen; these criteria have therefore not yet been finalized.

A radioactive waste repository in Switzerland will need to be licensed in an analogous manner to any other nuclear facility. This will involve applications for a general siting permit, a construction permit, an operating license and a permit for final sealing. The competent authority in such cases is the Federal Government which will submit relevant decisions for approval by parliament. Local authorities and communities grant permits only within the scope of normal planning regulations and may not revoke or refuse to acknowledge government-granted general permits.

16.2.2. Present Status of Site Reconnaissance Programme

For HLW, the work programme is not yet in the phase of specific site selection or characterization. Within the regional investigation programme, a broad siting area and sites for test drillings were identified on the basis of documented criteria. Most important here were seismic and tectonic criteria, availability of potential host rock at appropriate depths and avoidance of obvious conflicts with resources like thermal springs. Distance from population centers is not a selection criteria. In Switzerland there are today no really remote regions, and the demographic developments over relevant timescales of at least thousands of years are in any case not predictable. Later detailed selection of the limited area needed for surface facilities must, of course, pay close attention to planning requirements.

In general, for Nagra site selection in both HLW and LLW programmes, high emphasis is placed upon the geological, hydrogeological and geochemical characteristics of the site. There is a readiness to accept geotechnical problems which can be engineered around if the site in question has favorable safety-related characteristics. An important issue is the predictability of the site. Predictability here is meant in a spatial as well as in a temporal sense. This means that sparse measurements should be capable of extrapolation/interpolation in order to characterize adequately the entire area of interest, and that measurements should provide an understanding of the site geology which allows adequate prediction of future evolution.

The reconnaissance programme to date has involved surface mapping, large-scale geophysics, deep drilling with extensive downhole measurement programmes and also regional hydrogeological and hydrochemical investigations. This programme has been sufficiently documented on several occasions, with full details of the geophysical surveys and of the borehole programmes.

All exploration work to date is part of the Phase I regional programme. In the nineties, specific site(s) will be chosen for an intensive characterization from the surface (Phase II). Only thereafter will a shaft be sunk to provide the site confirmation data deemed to be necessary before any final license can be granted.

Today, however, experience in underground geotechnical studies is already being gathered in the Nagra Grimsel rock laboratory. This facility, which has been operated since 1983, lies some 450 m below the summit of the mountain Juchlistock in the Bernese Alps. The laboratory consists of around 1 km of horizontal 3.5 m diameter tunnels excavated by full-face drilling. An extensive research programme with many international collaborative projects is in progress. Specific experiments have been, or are, in progress in the following areas: cross hole hydraulics, in-situ stress measurements, large-scale ventilation tests, decompressed zone studies, *seismic and radar tomography*, *geoelectric* surveys, radionuclide migration and borehole sealing. Comprehensive documentation exists on the Grimsel facility and the research therein.

The above short summary indicates the breadth of investigations being undertaken for HLW disposal in Switzerland. For a small country with limited resources, in particular of suitably qualified technical staff, the correct balance between breadth and depth of project work must be maintained. Each new concept, each new host rock and each new study region requires a large amount of effort if the necessary high quality is to be maintained. In Switzerland, this problem is compounded by the fact that the LLW disposal programme (which is recognized to be of greater urgency) is also very diverse. Figure 16.1 gives an overview of all current areas being studied in the scope of Swiss repository programmes.

16.3. Key Issues in Geological Assessment

A prime objective of the Symposium to which this paper belongs is to look at "geological problems in waste disposal". In a project-oriented environment, these are more often referred to as "key issues" in disposal planning and implementation. It may not be necessary to solve definitively all of the key issues; it is possible to construct and license demonstrably safe repositories by avoiding specific issues by an appropriate choice of a site, design of the repository, or application of conservative performance assessment methodology. The issues to be discussed are as follows:

- role of geology in waste disposal
- contributions of geology to disposal planning
- importance of hydrogeology
- question of predictability (temporal and spatial)
- site selection and evaluation strategies.

16.3.1. The Role of Geology in Waste Disposal

Final repositories for radioactive wastes depend for their long-term performance on a variety of safety barriers. Figure 16.2 graphically illustrates that engineered barriers and geologic barriers can contribute in varying proportions to provide adequate safety and that a well designed system achieves large safety reserves by utilising all the barriers. It is important here to note that, without a geologic barrier, safety can be guaranteed only by introducing long-term institutional controls (cf French monitoring periods of 300 years for LLW). It is also important to note that the barrier lifetimes are crucial and that, for the very long decay times associated with HLW, the geologic barrier is that for which most data and observations are available for relevant timescales.

This does not mean that geological data of excessive exactness or detail are needed. At shorter times (up to thousands of years) the geologic medium mainly provides a suitable environment for ensuring adequate performance of the near-field engineered barriers (e.g. erosion protection, limited water flows). At very long times where releases from the near field may occur, decay has reduced the toxicity of the inventory and many of the remaining long-lived nuclides exhibit poor solubility and high retention. Accordingly, we need to be able to characterize the geology and its long-term evolution, but only to the extent directly affecting predicted repository performance.

16.3.2. The Contributions of Geology to Disposal Planning

Geological information is required as input for the civil engineer, who must design and construct the repository, and for the performance assessor, who must analyse the behaviour over time. The engineer's task is relatively well known; based on extensive experience in underground construction, he can specify which rock mechanical, hydrogeological and geothermal data he requires. The main novel problem is that he may be required to predict the behaviour of the engineered system over longer timescales than usual, and also without the possibilities of recurring inspection and maintenance. This can affect the type of geotechnical input data needed, in particular, with respect to long-term rock creep parameters.

The remaining contributions of geology to repository projects are of direct relevance for safety. The safety-relevant processes and the corresponding geological input for their characterization can be listed as follows:

- physical protection of the engineered repository system against natural and man-made influences - erosion mechanisms, tectonic movements, rock creep,
- limiting radionuclide release from the near field - groundwater flows (hydraulic conductivities, gradients), hydrochemistry,
- retention of nuclides close to the repository (≈100 m, i.e. in the rock volume which can be characterized from within the repository) - groundwater flows, water flow systems (porous media, discrete fractures, fracture zones), geochemistry, hydrochemistry,
- retention of nuclides in geologic media further from the repository (i.e. the region which must be characterized from the surface) - as in the previous list plus larger scale regional geologic faulting,
- dilution in aquifers - regional groundwater flows (volumes, directions), contrasts in

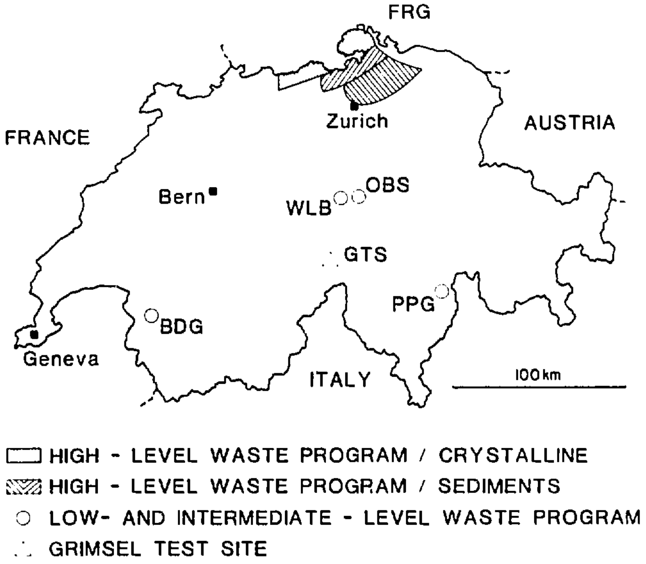

Figure 16.1. Nagra projects - situation map.

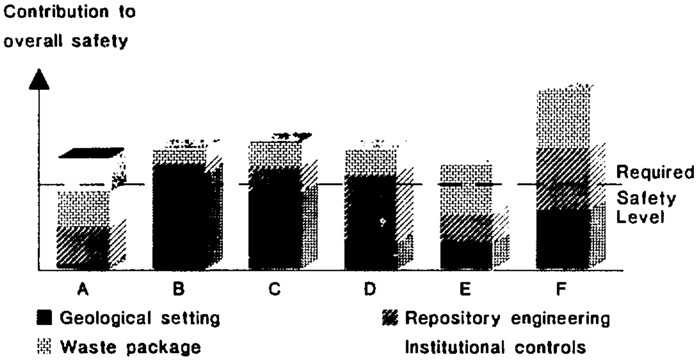

Figure 16.2. Relative safety contributions in a multibarrier repository system.

hydraulic conductivities, flow systems in the aquifers, and

- dilution in river sediments and rivers - discharge zones, volumetric flows, variations with time.

From this list, it is apparent that any repository implementation plan must include a proper concept for geologic investigations, and that hydrogeologic characterization is the component of prime importance. This latter fact often receives too little attention in waste disposal programmes with the result that *traditional* geologic disciplines like mineralogy and petrography can become overemphasized.

16.3.3. Importance of Hydrogeology

During the development of repository planning, increasing emphasis has been devoted to determining the hydrogeologic conditions at potential sites. The importance is demonstrated by the above lists showing how all aspects of system performance depend upon water flows. Intensive efforts in hydrogeology have also been necessary because of the choice of low permeability media as potential host rocks. In such media, water movements are the exception and are correspondingly difficult to characterize in a manner representative for a repository-sized region. This has led to developments in field testing techniques, in analysis of hydraulic tests, and in large-scale computer modelling of hydrogeological regimes. In Swiss work, hydraulic testing has been the single most cost-intensive component of borehole testing programmes, and hydrogeologic modelling is a major activity within all performance assessments. Much intellectual and practical effort has also been devoted to characterizing the fine-scale flow systems which so critically determine the transport properties of radionuclides dissolved in groundwater.

In deciding upon the geologic data requirements, direct use has been made of iterative hydrogeological modelling based upon a structural geology model which is revised in the light of results from the field. The geologic and hydrogeologic models for a particular host rock in a specific siting region require the following input:

- regional geologic structures (stratigraphy, lithology, petrography, tectonics),
- regional hydrogeology (infiltration/exfiltration zones, aquifers, hydraulic potential field, conductivities, hydrochemistry, isotope hydrology),
- host-rock characterization (geometry, lithology, geochemistry, hydrochemistry, tectonic, flow systems, conductivities), and
- neotectonics.

For all of these we must, in principle, know the current conditions, potential changes caused by repository construction and operation, and long-term evolution. This seemingly insurmountable task of data collection can be restricted to a feasible level only by continually assessing the role of the geologic parameters in determining repository performance or safety. By doing so, it becomes possible to use data of differing completeness and quality and from different sources.

Direct measurements at the specific site will be performed for key parameters, although sufficient data density, accuracy and representativity will always remain a problem. Further geotechnical measurements can be performed in the general region, elsewhere in analogue situations, or in the laboratory; in all cases, the justification of extrapolation to repository conditions must be discussed. Key parameters can also be derived from calculations based on raw data (for example derivation of hydraulic conductivities from pressure histories); here the main problems are the validation of the conceptual and calculational models involved. Finally, some data will always depend on the use of expert opinion to evaluate results which leave room for interpretation. Although semi-formalized methodologies have been developed to elicit such opinions, convincing technical personnel, safety authorities and public of their acceptability is never easy.

16.4. The Influence of Explorability on Site Investigation Strategies

Uncertainties in the results of performance assessments mirror uncertainties in their input data. Input uncertainties will always be inherent in the geologic data because extrapolation is required in space and in time. In recent Swiss work, much attention has been devoted to attempting to characterize the explorability of different geologic media since our ability to adequately characterize the host rock may be a critical criterion in site selection. Firstly, the reliability of our measurement tools is assessed on a host-rock specific basis. The tools are subdivided into those which can be employed from the surface, in a single borehole, using cross-hole techniques and at depth from shafts, adits and underground laboratories. This classification is important because a site investigation strategy usually develops through these stages, and at each stage one wishes to estimate the potential for success during subsequent exploration.

The particular cases recently studied in depth in the Swiss programme have been the two proposed potential sedimentary host rocks for HLW, namely Opalinus clay and lower freshwater Molasse. These are interesting and contrasting examples since the former is a very tight, relatively homogeneous formation of limited extent and the latter is much more extensive but is much more heterogeneous on the macroscopic scale, containing both tight marls and more transmissive sandstones.

For each alternative, a phased site investigation strategy is being developed. In a first phase involving limited field work, key questions are addressed in order to estimate the effort required for characterization at each further stage and to assess the resulting residual uncertainties on ultimate site suitability. The second phase (intended to localize facilities, allow more reliable safety analysis and demonstrate site suitability fairly conclusively) involves more intensive exploration from the surface. The third phase comprising complete characterization from underground is time consuming and expensive. All preceding work should be aimed at reducing the residual risks of failure at this stage. It is recognized, however, that a finite probability of site rejection based on geological findings in Phase 3 will always remain.

In the preceding sections we have touched upon different points concerning the characterization of a particular potential repository site. Many features are of importance and it is possible that one of these, or more likely a combination of them, may be found during the investigations to be so unfavourable that a site can no longer be recommended for hosting a repository. It is important to recognize as early as possible if this situation occurs; accordingly, it is important to formulate initial rejection criteria early and to continually review these. Unfortunately the defense in-depth, multibarrier philosophy of repositories tends to make obvious, single rejection criteria unlikely. This emphasizes the role of repeated, integrated performance assessments which are aimed at re-evaluating the contributions of geology to final overall safety and at quantifying the acceptable levels of key parameters.

If a site should prove unsuitable at any point, alternatives should be available. Therefore it is also important to formulate a global strategy determining the number of sites to be studied or more generally the diversity of the repository development programme. This question is discussed in the final concluding section.

16.5. Site Evaluation and Selection Strategies

What are the advantages and disadvantages of a very diversified approach? One of the main resulting problems is obvious. The high level of technical effort required, together with the intensive accompanying work to ensure full public information, place large strains on the manpower and financial resources supported by a small nuclear programme. Looked at from another angle, this can mean that available effort may be in danger of becoming so diluted that effective, first-class project work becomes difficult and projects are in danger of becoming undercritical.

Perhaps the most potentially harmful effect of a diversified approach is, however, that one can give the impression that a *best* or *safest* option is being sought. Of course, we are seeking options which demonstrably offer large safety reserves and which are not obviously technically inferior to other available concept choices. But the selection procedure: (a) is necessarily incomplete in that not all conceivable options can be studied, and (b) involves such a high component of human judgement that no irrefutable proof that a best option has been chosen will ever be possible.

On the other hand, a programme which begins with a broad approach and successively narrows in on the basis of serious, well-documented scientific investigations does have very positive aspects. The project staff involved gain wide experience and specific knowledge which is invaluable in explaining the choices ultimately made. The creative efforts involved in examining the strengths and weakness of a range of technical options increase confidence that studies of the finally selected concept will be as complete as possible. Although the general public appears to give relatively little credit for a structured selection process, it is important to have recognition that logical selection criteria have been applied. Crucial in this respect is the timely production of proper documentation on the process. Of course, it is sometimes difficult to document decisions based partly on human judgement and the documentation can always give rise to controversy; much more opposition, however, results from a lack of documentation.

In conclusion, we attempt to list the lessons we have learned concerning selection of disposal concepts and sites based upon the knowledge and experience which we have gained in the last 10 or more years.

- The broadest possible approach is to be recommended at the early screening phase.

- The more restricted choice necessary for specific field investigations (including field work) must weigh against one another:
  - — the demands on time, manpower and resources
  - — the requirements to retain enough options to ensure with high probability that at least one viable choice is included.
- The selection process should be well documented, with emphasis being put upon the goal of finding acceptable solutions with large safety reserves rather than a single best solution.
- As soon as confidence is sufficiently high that a chosen concept could be successfully implemented, the parallel procedure sketched above should be dropped in favour of a sequential procedure. The additional concepts or sites become back-up solutions in case the first priority option does not lead to success.
- Resources can then be concentrated upon the chosen top priority solution. The depth of studies associated with disposal planning today imply that a small programme can devote adequate effort at the detailed site characterisation and project implementation phases to only one main option.
- In the most pessimistic scenarios, this concentrated effort on one potential solution can lead to a delay in repository implementation and to increased costs. However, the nuclear power programme can, if necessary, accept both drawbacks with no irreparable damage to the disposal strategy.

The generalized remarks made above are, of course, based upon experience in Switzerland, a small densely populated country with varied, complex geology and a limited nuclear programme. It would be interesting to discuss their applicability, or perhaps other variations, in some of the advanced nations with larger waste disposal programmes.

Chapter 17

Geological Aspects for Potential High Level Waste Repository Site in Taiwan

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17.1. Abstract

Due to the collision of the oceanic Philippine Sea plate and the continental Eurasian plate, active volcanic and seismic disturbance exists in Taiwan. Although the active deformation of the bedrock has calmed down, rapid land uplift and frequent strong earthquakes still indicate the continuous geological unrest in Taiwan. It shows that the peak tectonic activity has been located in the eastern Taiwan, and the seismic intensity of southern Taiwan may represent an alternative option. More detailed planning of the geological investigation must await the results of ongoing work. The availability and accessibility of potential candidate sites, and alternative uses of the land must also be considered in the selection of candidate sites for investigation.

17.2. Introduction

Taiwan has a severely limited supply of natural energy resources; virtually all fossil fuels used for power generation are imported, and hydroelectric power, although fully developed, is of minor importance in the national power pool. Because of the heavy dependency on energy resources, the development of nuclear energy has always been one of the top priorities in the energy policy of the Republic of China. The nuclear energy policy is expected to bring Taiwan the stability of energy supply, the reduction of power costs, the development of national industry, and an impulse buildup of strong economics. As in other industrialized countries, the back end of the nuclear fuel cycle, which means high-level waste (HLW) including spent fuel in Taiwan, is an important task in the Taiwan nuclear industry. According to the recently approved Radwaste Management Guidelines (Radwaste Administration, 1988), the major targeted milestones of HLW management in Taiwan are:

- Completion of safety analysis and environmental impact evaluation of an interim storage facility, and commencement of the interim storage facility before 2001,
- Continuous planning of final disposal alternatives for HLW, and a proposed feasibility study and implementation program as soon as possible.

Since the London Convention in 1983, the international consensus favors land-based geological disposal for HLW, which will inevitably be followed in Taiwan. Nevertheless, the island of Taiwan and adjacent areas represent one of the geologically most active regions in the world (Suppe, 1981). To provide full radiological safety in an entirely passive disposal system, extensive and comprehensive studies of the geological conditions of Taiwan are required for the proposed geological disposal of HLW in an underground repository.

Taiwan is situated at the eastern margin of continental Asia bordering the Pacific Ocean. It contains one of the Tertiary mountain chains of the Earth with rapid uplift of the land and conspicuous earthquake activity. The oceanic Philippine Sea plate moves towards the North and Northwest and overrides the continental Eurasian plate on the west side and is pushed beneath that plate in the north (Ho, 1982). The resulting mechanism may cause future geological disturbance and instability in Taiwan (Chi, et al., 1981; Teng and Wang, 1981).

17.3. General Geology of Taiwan

The general geology of the Taiwan region can be divided from west to east into four major units (see Figure 17.1):

(1) An essentially passive, continental Western Platform, submerged under the Taiwan Strait, characterized by a block structure and rifting with a relatively thin series of cover rocks. This unit has escaped from major deformation for the last 30 million years.

(2) An intermediate Foreland, consisting of the Western Coastal Plain and the Western Foothills, characterized by rocks of westward trending deformation with both folding and faulting.

(3) The Central Highlands, composed of metamorphic cover rocks as well as basement rocks. All rocks show strong deformation, and the present position of the basement rocks indicates rapid uplift and violent erosion on the order of ten kilometers during the past six million years.

(4) The Eastern Coastal Range, taken to the leading edge of the Philippine Sea plate overriding the buried eastern edge of the continental Asian plate in the west. This Range is separated from the Central Highlands by the Eastern Longitudinal Valley.

The active deformation of the bedrock, especially the cover rocks of the Foreland, seems to have calmed down about 130 thousand years ago, as evidenced by the near horizontal, undeformed younger sediments of the Coastal Plain. However, rapid land uplift and frequent strong earthquakes still indicate the continuous geological unrest in Taiwan. From the consistent geological arrangement, it shows that the peak tectonic activity has, for the last 30 million years, been located in eastern Taiwan, and seismic intensity has decreased towards the West. All available data suggest that this situation will persist throughout the service life of a repository.

17.4. Potential Host Rocks for Repository

Potential host rocks for a safe repository may be found at appropriate depths in some areas of Taiwan, ranging from deformed rocks of the crystalline basement to shales and mudstone in the cover series (see Figure 17.2). Therefore, the availability of host rocks is not seen to be a critical issue. However, the host rocks can not be evaluated only on their physical and chemical properties but also on their geological context and local socio-economic factors.

Based on mechanical properties, the rocks in Taiwan can be classified as hard rocks and soft rocks. Man-made openings in hard rocks are usually expected to persist for long times, thus providing safe accessibility and a smooth retrievability. Although the hydraulic conductivity in hard rocks is normally very low, the solute transport in the fractures of hard rocks is usually complicated and difficult to model. Such fracturing can extend to considerable depth; therefore, proper evaluation of fracturing is a major task of site investigation and is critical for safety and performance assessments in hard rock geology.

Hard rocks occur mainly in the Eastern Coastal Range and in the Basement of the Central Range. All information indicates that the Western Platform appears to offer considerable potential for a safe repository in hard rocks, and the Penghu Islands seem to have basement rocks that are reasonably accessible (Chen, 1973; Jahn, et al., 1976; Yen, 1987). Outside the Western Platform, other hard rocks may deserve some consideration. Andesite and dacite in Northern Taiwan mark dormant volcanism, but the associated high geothermal gradient may exclude a deep repository in this area. The accessible quartzitic sandstones in northern Taiwan are hard, brittle, and fractured. Further study may be required for more definite evaluation on these hard rocks as potential host rocks for the HLW repository.

Information on the hard rocks of the Basement Ranges is rather limited. The best access to such rocks appears to be the granitic gneiss on Kinmen Island, which can be correlated with the Fukien Granite of adjacent continental China (Chen, 1974; Jahn, 1974). These occurrences probably would offer the best opportunity for geological and technical studies without resort to deep drilling simply due to the absence of significant cover rock. The rock on this island has many aspects comparable to the crystalline host rocks in Sweden, Canada, Finland, etc. The technical data so far developed in these countries could be directly and readily applicable.

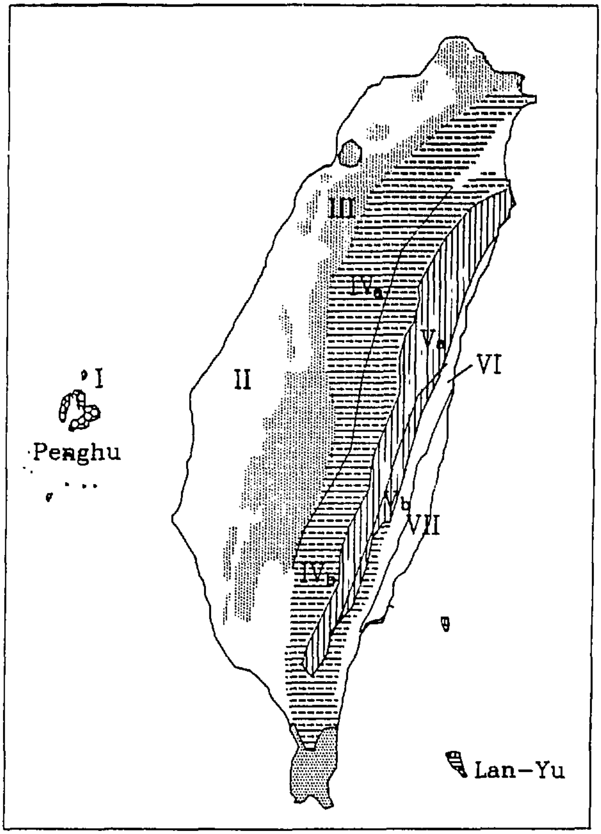

Figure 17.1. Tectonostratigraphic belts of Taiwan (modified from Ho, 1986).

I. Penghu Islands, Pleistocene on Western Platform.
II. Western Coastal Plain, Pleistocene on Foreland.
III. Western Foothills, fold-thrust belt, mainly of Neogene clastics.
IV. Central Highlands
V. Eastern Basement Ridge
VI. Eastern Longitudinal Valley.
VII. Eastern Coastal Range, fold-thrust belt, mainly of Neogene Volcanoclastic and turbiditic sediments.

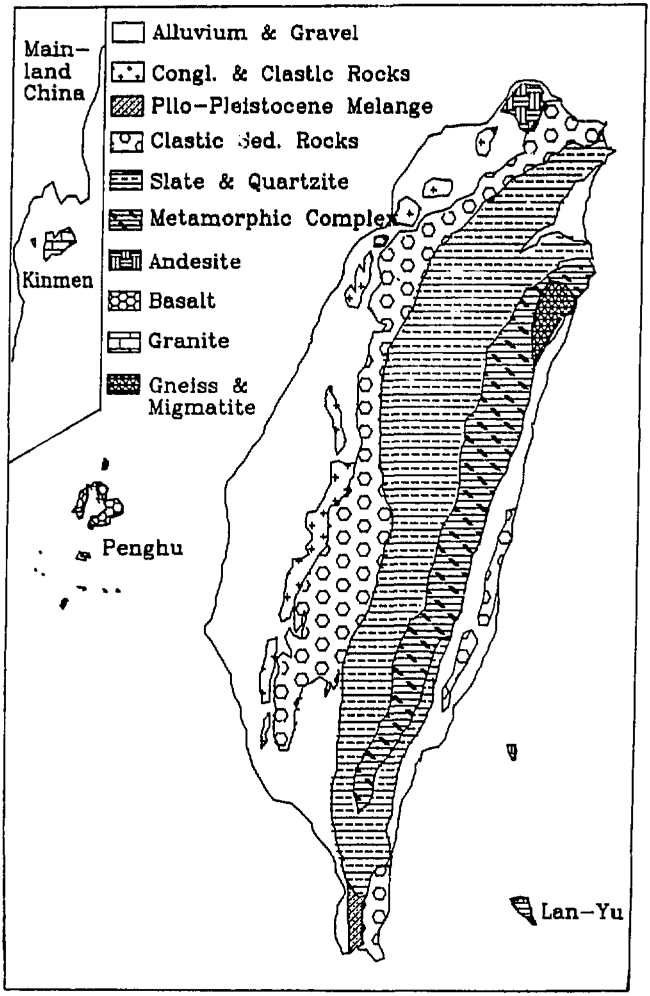

Figure 17.2. Distribution of potential host rocks for HLW repository (Ministry of Interior, 1981).

The eastern occurrences of hard rock have been subjected to active tectonism, i.e. rapid uplift and continued fracturing and faulting. Erosion presently proceeds with an average vertical rate of about 5 mm per year (Li, 1976). None of these factors could ever favor eastern Taiwan as an appropriate location for a repository site. Even worse, eastern Taiwan appears to be problematical as a host for a repository when considering transportation and other practical matters.

Regarding soft rocks, including mudstone and shale, they usually have low hydraulic conductivity, coupled with higher transport porosity and stronger absorption than most hard rocks (Nuezil, 1986). Additionally, fractures in the soft rocks generally are expected to be rare, notably at depth. On the other hand, plastic rocks and clays will tend to close around emplaced waste packages, and require particular consideration during the construction and operation of the repository structure. The thick Nanhua mudstone found in the Western Foothills is easily eroded and forms a vast area of typical badland morphology (Chou, 1971). It reaches a depth in excess of five kilometers. This mudstone was found to contain chlorite, illite, smectite, and probably kaolinite (Wang, 1970), which could serve as good geological barriers because of their sorption capacity.

Shale is widespread over the Foreland, both beneath the Western Coastal Plain and in the Western Foothills (Chou, 1980; Ho, 1975). Based on its low hydraulic conductivity, low porosity, and high sorption capacity, it is expected to be quite an ideal host rock. However, the rate and extent of future denudation is a fundamental concern for both mudstone and shale. Therefore, information on the erosion processes in the Foothills, the Plain, and on the uplift of the Foothills relative to the Coastal Plain is of vital interest. Moreover, the mechanical behavior of these soft rocks may call for special attention to the techniques of HLW emplacement, operation and restoration, and to the response of the host rocks to future tectonic activity.

17.5. Potential Candidate Areas

A tentative sequential siting process for a repository in Taiwan is given in Table 17.1 with five steps proposed. For each step, key influencing factors are identified and the preferred alternative is suggested. However, other non-geological factors, e.g., availability and alternative uses of the site, are not addressed. At this stage, several important geological factors, i.e.,

(1) The foreseeable depth of future denudation,

(2) Geological unrest vs. predictability,

(3) The barrier performance of the local cover rocks, and

(4) The performance of the local host rocks, are not actually known with confidence.

Accordingly, any conclusion drawn from this list may rely heavily on preliminary and crucial assumptions regarding these factors.

Two different concepts for the final disposal of HLW in Taiwan are proposed: (a) a mined repository in hard rock or shale at a depth of less than 1 km, and (b) a deep borehole arrangement (primarily in mudstone). The depth of a mined repository is technically limited by the prevailing geothermal gradient, i.e. higher rock temperatures at depth with decay heat from the HLW may degrade the integrity of a safe repository. Otherwise, a mined repository has technically well-known elements, most of which are in practical use in other fields and have been extensively tested in laboratories and in the field. For soft rocks like mudstone, disposal in boreholes at greater depths of about 2 km is suggested for deeper denudation. This option is judged to be realistic primarily based on the techniques in exploration drilling. The actual techniques have not been scrutinized, and are rather limited even if any development is presently undertaken. This situation largely determines the general course of investigations suggested here. Basically the geological situation in Taiwan determines the technical options, and these in turn determine the course of further work. Fundamental factors are the persistent geological unrest and the resulting future denudation.

The choice of a geological unit is based on the assumptions that the Western Platform offers the best chances of limited future denudation and geological unrest, and that an adequate host rock can be found there. Because of the number of uncertainties involved, these assumptions require considerable study for definite confirmation or rejection of a disposal unit.

Regarding the general area for exploratory work within the Western Platform essentially involves practical considerations. Not only is the island of Taiwan easily accessible, but exploration work is also more effective and economic on land than offshore. The decisive factor at this point will be the cover rocks and their potential barrier function. If the barrier function of the cover rocks can be ignored and accessibility of the western offshore islands of the Platform can be solved, these islets may appear more attractive for closer investigation.

Table 17.1. Siting process of nuclear waste repository in Taiwan

Phase	Alternatives		
1. **Concept of Repository**	**Mined**[2]	Deep-Borehole	
Denudation/10^6 yrs†	< 500 m?	>500 m?	
Host rocks	likely	likely	
Tech. availability	yes	possibly	
Int'l safety review	yes	no	
Int'l R&D	extensive	minor	
2. **Geological Unit**	**Platform**[2]	Foreland	Foothills
Denudation	??	< ???	< ???
Geological unrest	??	< ???	< ???
Host rock	likely	likely	likely
3. **General Area**	**Taiwan**[2]	Offshore	W. Islets[3]
Cover rocks	yes	yes	no
Practical aspects	+	-	+/-
4. **Working Area**	**w/ Cover Rocks**[2]	w/o Cover Rocks	
Cover barriers	??	No	
5. **Candidate Site??**			

Note:
1. Decisive factors.
2. Preferred alternative.
3. Conditionally attractive.

As for the choice of working area, it is assumed that the cover rocks can provide an additional multiple barrier. In the critical geological environment of Taiwan, this is an important consideration. The data from petroleum exploration in the Taiwan Strait may provide priceless insight in answering this question.

The last stage in selecting a candidate site for comprehensive investigation will essentially require a combination of fundamental and practical considerations. Because of technical uncertainties involved and the long-term national policy required, the site selection work for the HLW repository has a long way to go.

17.6. Conclusion

A rather stable tectonic framework and possible crystalline basement may suggest some parts of the Taiwan Strait on the Western Platform for potential repository area. Cover rocks can also provide additional geological barriers for valuable safety. Deep emplacement in mudstone represents an alternative disposal option against the denudation problem. More detailed planning of the geological investigations in Taiwan must await the results of ongoing work. The availability and accessibility of potential candidate sites, and alternative uses of the land must also be considered in the selection of candidate areas and sites for investigation.

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Chapter 18

Geological Aspects of the British Programme for Deep Disposal of Nuclear Wastes

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18.1. Introduction

In March 1989, UK Nirex Ltd., the company responsible for disposing of Britain's radioactive wastes, announced that it intended to carry out geological investigations of the Sellafield and Dounreay nuclear sites to determine their suitability to host a deep repository for low and intermediate level wastes. At both sites the investigation would be concerned with a repository located in basement rocks underlying sediments, at depths between about 500-1000 m. Sellafield, renowned for its nuclear fuel reprocessing facilities, and Dounreay for the experimental fast-breeder reactor, are both coastal sites (Figure 18.1) whose predicted deep geological structures have not yet been confirmed in detail by drilling. The nomination of these two sites took place after a two year site selection programme which included geological comparisons and predictive safety assessments based, in part, on geological information. This resulted in a short-list of preferred sites, from which Sellafield and Dounreay were selected for initial scrutiny. If both these sites prove unsuitable, other sites will be considered for investigation.

A programme of exploratory site investigations is scheduled to begin in mid-1989, and will provide information for the selection of a single site for detailed, long-term characterization during the 1990's. This process will include the construction of an underground research laboratory, and the progressive exploration of the rock volume in conjunction with the excavation of the repository, which is planned to be operational by 2005. During this period, Nirex will undertake continuous iterations of its safety assessment programme, which is designed to analyze the long-term performance of a repository, and consequently to focus both research and site investigation on issues that might be critical to the radiological safety of disposal. The principal regulatory authority in Britain is Her Majesty's Inspectorate of Pollution within the Department of the Environment, and its equivalent body in Scotland. When Nirex submits their proposals to the regulators they will be considered by HMIP and the other Authorising Departments, using their own, independent, assessment programme. Although the methodologies differ somewhat, both Nirex and HMIP will make use of similar conceptual approaches for predicting future geological evolution of a repository, and both will have recourse to the same site-specific geological data for their models. These approaches have been developed via research programmes sponsored by both organizations, and by participation of the many UK scientists involved in international projects. Much of the conceptual basis for predicting the geological behavior and long-term evolution of deep repositories is now held in common by all national authorities managing nuclear wastes, and relies on levels of understanding that are often at the forefront of our knowledge in the earth sciences. This paper examines the geological background which has led up to the the present situation, and looks at the main geological issues which arise now that firm proposals exist for disposal of Britain's nuclear wastes at specific locations.

18.2. The Wastes and the Repository

In 1981, the UK Government decided that high-level waste (the vitrified by-product of reprocessing nuclear fuel) should be stored for about 50 years to allow much of the activity to decay prior to disposal. However, there was no call for storing the very much larger volume of lower activity waste. Until 1987, the disposal

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*Now with Intera-ECL, Melton Mowbray, Leicestershire, UK.

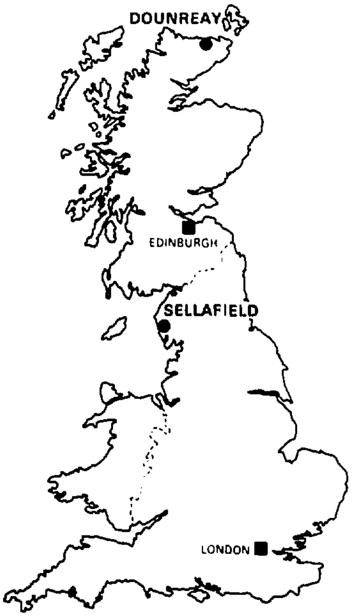


Figure 18.1. Location of the two sites scheduled for preliminary investigation for a deep radioactive waste repository.

option was to have been shallow-land burial for the lower level component, which represents the majority of these wastes, and deep disposal for the more active of the intermediate level wastes, but in May of that year Nirex cancelled site investigations at four potential repository sites in England, and UK policy became that of eventual deep disposal of all nuclear industry, commercial, and research wastes.

The wastes concerned can be categorized approximately as follows:

(1) Operational low level waste (gloves, filters, laboratory equipment, and the like) and reactor decommissioning low-level waste (concrete and steelwork). This will be packaged in 200 liter steel drums, or in larger steel boxes.

(2) Operational intermediate level waste (fuel cladding, fuel element debris, solidified sludges and ion-exchange materials from clean-up of liquid effluents, items of redundant plant and equipment, etc) and reactor decommissioning intermediate-level waste (items from within reactor cores, including graphite and pressure vessel steel). This will mostly be packed into 500 liter steel drums, or steel boxes. Very large items may be contained in self-shielded concrete boxes.

The repository will be designed by Nirex to hold about 2 million cubic meters of waste by the time it is sealed around 2055, assuming that much of the low-level waste can be compacted prior to disposal (UK Nirex Ltd., 1987, 1989). Approximately one third of the waste will arise from the decommissioning of nuclear reactors. The combined effects of radioactive decay heating from some of the wastes, chemical reactions in the wastes and barriers, and the geothermal gradient may lead to parts of the repository being subjected to average temperatures of up to 80°C. In the Nirex proposals, wastes will be disposed of in mild steel containers which will be vented as necessary to permit the release of gases generated by the degradation of organic materials in the wastes, and by anaerobic corrosion of metals in the waste and containers. The proposed design of the repository will make use of considerable volumes of cementitious material both as grout in and around waste container, and as bulk backfill. This will provide a controlled high pH chemical environment around the waste which ensures that the solubility of many of the radionuclides is restricted to low levels, and provides a large surface area in the 'near-field' zone of the repository for sorption of radionuclides (Hodgkinson and Robinson, 1987; Saunders, 1988; UK Nirex Ltd., 1988). The cement backfill will be designed to be sufficiently porous and permeable to allow relatively rapid chemical mixing within the near-field, to take full credit for its buffering potential.

Although the full reference inventory of radioactivity in the wastes is substantial (Table 18.1) only a limited number of radionuclides contribute to the overall activity of the repository (Figure 18.2). These are ^{90}Sr, ^{137}Cs, and ^{63}Ni in the period up to about 1000 years, ^{59}Ni and ^{93}Zr in the intermediate timescale, and ^{238}U and ^{226}Ra at times greater than a few million years (Billington, et al, 1989). However, performance assessments which account for the mobilization and migration rates of the full spectrum of radionuclides in the repository show that the significant nuclides of concern are (depending on groundwater transit times from the repository to the surface) ^{36}Cl and ^{129}I in the short term, ^{126}Sn in the period between 104 and 106 years, and ^{226}Ra.

Both sites now being investigated would have a repository situated in hard, fractured basement rocks. Designs for such a facility (Figure 18.3) envisage that most of the wastes would be emplaced in large caverns, 25 m wide, 35 m high and about 250 m long. A total of 26 such vaults would be required which, together with service galleries and four access shafts, would require the excavation of more than 6 million cubic meters of rock (UK Nirex Ltd., 1989). Prior to the selection of sites, design work was also assessing options for repositories in anhydrite, stiff clays and chalk. Options for siting the repository offshore in deep sediments and hard rocks below the sea-bed were also assessed.

18.3. The Options for Deep Geological Disposal in the UK

Understanding of the types of low groundwater flow regime found in deep clay formations and massive fractured rocks has increased immensely in the last ten years, almost entirely as a result of research into radioactive waste disposal. Coupled with a greater confidence in modelling such low-energy, low-flow environments, this has caused a reappraisal of the "salt-clay-granite" approach to selecting deep repository sites, built on requirements for disposal of high-level, heat-emitting wastes. This had placed great emphasis on the need for a low permeability, thermally stable host-rock. It became apparent that the selection of sites for deep disposal of less thermally active wastes needed to be based more on defining suitable large-scale hydrogeological environments, with the focus on long groundwater return times, a very slowly evolving regional groundwater regime, and a reduction in emphasis on the host rock itself (Chapman et al., 1986, 1987). The features of the geological environments thought to be most suitable are characterised by:

(1) A high level of confidence in the predictability of the local and regional hydrogeology, with the minimum of geological complexity,

(2) Long groundwater 'return' paths to the surface, preferably resulting in progressive mixing with older, deeper waters, or leading to discharge to the sea. Such slow groundwater movements are usually associated with areas of low regional hydraulic gradient and/or low hydraulic conductivity,

(3) Ease of construction to allow for economic repository design, and

(4) Meeting many other widely accepted guidelines regarding the regional and local significance of mineral deposits, geothermal gradients, seismicity, formation depth, etc.

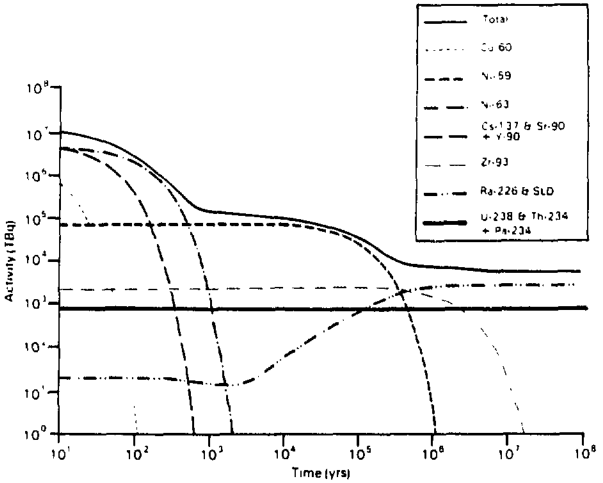
In the UK, the types of geological environment containing rock formations which meet the above requirements can be broken down as follows (Chapman et al., 1986):

(a) *Inland Basinal Environments:* deep sedimentary basins containing mixed sediments with a high proportion of low permeability formations (mudstones, evaporites, etc.). Regional groundwater flow would be mainly confined to any aquifer units, and would tend to be down dip with sub-vertical fluxes across the low permeability units at very low advection rates or, where there is little or no advection, at rates dominated by diffusion.

(b) *Seaward Dipping and Offshore Sediments:* similar in concept to (1), with groundwater movements expected to be

Table 18.1. Reference assessment inventory.
Radionuclide content of the 2,000,000 m^3 of wastes assumed
for disposal over 50 years

Nuclide	Half-life	Total Inventory		Operational Waste		Decommissioning	
		LLW (TBq)	ILW (TBq)	LLW (TBq)	ILW (TBq)	LLW (TBq)	ILW (TBq)
H-3	12.35y	1.3×10^{2}	6.8×10^{3}	3.4	6.3×10^{3}	1.3×10^{2}	5.4×10^{2}
C-14	5730y	4.8×10^{1}	6.6×10^{3}	4.5×10^{1}	6.5×10^{3}	3.8	7.9×10^{1}
Cl-36	3×10^{5}y	5.7×10^{-2}	2.6	3.0×10^{-3}	1.3	5.4×10^{-2}	1.3
Ca-41	1.4×10^{5}y	5.8×10^{-1}	1.3	0	3.0×10^{-2}	5.8×10^{-1}	1.3
Co-60	5.27y	3.7×10^{1}	2.9×10^{6}	3.3	2.4×10^{6}	3.3×10^{1}	4.3×10^{5}
Ni-59	7.5×10^{4}y	6.0×10^{-2}	6.1×10^{4}	3.1×10^{-3}	6.1×10^{4}	5.7×10^{-2}	4.4×10^{2}
Ni-63	100y	8.3	4.2×10^{6}	2.7	4.2×10^{6}	5.6	4.4×10^{4}
Se-79	6.5×10^{4}y	3.2×10^{-2}	1.1×10^{1}	1.1×10^{-5}	1.1×10^{1}	3.2×10^{-2}	9.4×10^{-2}
Sr-90	29.1y	1.0×10^{1}	1.4×10^{6}	8.4	1.3×10^{6}	1.9	8.7×10^{4}
Zr-93	1.5×10^{6}y	8.6×10^{-2}	2.0×10^{3}	0	2.0×10^{3}	8.6×10^{-2}	7.0
Nb-93m	13.6y	0	1.6×10^{3}	0	1.6×10^{3}		
Nb-94	2×10^{4}y	5.4×10^{-2}	7.7×10^{3}	2.5×10^{-9}	7.7×10^{3}	5.4×10^{-2}	1.0
Tc-99	2.1×10^{5}y	4.3×10^{-1}	5.7×10^{2}	1.1×10^{-1}	5.3×10^{2}	3.2×10^{-1}	4.7×10^{1}
Pd-107	6.5×10^{6}y	4.3×10^{-3}	5.7	1.1×10^{-3}	5.3	3.2×10^{-3}	4.7×10^{-1}
Ag-108m	127y	3.0×10^{-2}	4.2×10^{-1}	3.0×10^{-2}	4.2×10^{-1}		
Sn-126	10^{5}y	3.2×10^{-2}	2.0×10^{1}	1.8×10^{-5}	2.0×10^{1}	3.2×10^{-2}	9.4×10^{-2}
I-129	1.57×10^{7}y	3.6×10^{-5}	1.5	3.4×10^{-5}	1.5	1.6×10^{-6}	4.7×10^{-2}
Cs-135	2.3×10^{6}y	3.2×10^{-1}	3.1×10^{1}	1.3×10^{-5}	2.9×10^{1}	3.2×10^{-1}	1.7
Cs-137	30y	2.9×10^{1}	2.3×10^{6}	2.4×10^{1}	2.2×10^{6}	4.5	8.7×10^{4}
Sm-151	90y	4.3×10^{-3}	1.4×10^{4}	4.3×10^{-3}	1.4×10^{4}		
Pb-210	22.3y	1.6×10^{-2}	1.9	1.6×10^{-2}	1.9		
Ra-226	1600y	1.6×10^{-1}	2.0	5.1×10^{-2}	1.2	1.0×10^{-1}	8.7×10^{-1}
Ra-228	5.75y	3.7×10^{-3}	1.9	3.7×10^{-3}	1.9		
Ac-227	21.77y	5.4×10^{-6}	6.2×10^{-2}	5.4×10^{-6}	6.2×10^{-2}		
Th-228	1.9y	3.7×10^{-3}	1.9	3.7×10^{-3}	1.9		
Th-229	7.34×10^{3}y	0	3.6×10^{-1}	0	3.6×10^{-1}		
Th-230	7.7×10^{4}y	4.8×10^{-5}	4.0×10^{-2}	4.8×10^{-5}	4.0×10^{-2}		
Th-232	141×10^{10}y	3.7×10^{-3}	3.0	0	2.1	3.7×10^{-3}	8.7×10^{-1}
Pa-231	3.28×10^{4}y	1.0×10^{-5}	9.9×10^{-2}	1.0×10^{-5}	9.9×10^{-2}		
U-233	1.58×10^{5}y	0	9.5×10^{-2}	0	9.5×10^{-2}		
U-234	2.45×10^{5}y	1.1×10^{1}	5.8×10^{1}	1.6	3.5×10^{1}	9.6	2.4×10^{1}
U-235	7.04×10^{8}y	5.9×10^{-1}	8.1×10^{1}	2.7×10^{-1}	7.8×10^{1}	3.2×10^{-1}	2.5
U-236	2.34×10^{7}y	8.8×10^{-5}	3.7	8.8×10^{-5}	3.7		
U-238	4.47×10^{9}y	2.5×10^{1}	2.0×10^{2}	1.6×10^{1}	1.4×10^{2}	9.6	5.9×10^{1}
Np-237	2.14×10^{6}y	3.2×10^{-2}	3.4×10^{1}	8.8×10^{-5}	3.4×10^{1}	3.2×10^{-2}	1.7×10^{-1}
Pu-238	87.7y	1.9	1.7×10^{4}	8.5×10^{-1}	1.5×10^{4}	1.1	1.3×10^{3}
Pu-239	2.41×10^{4}y	2.9	1.7×10^{4}	1.7	1.1×10^{4}	1.2	6.0×10^{3}
Pu-240	6537y	3.0	1.5×10^{4}	1.7	1.1×10^{4}	1.3	3.9×10^{3}
Pu-241	14.4y	2.1×10^{1}	5.7×10^{5}	3.1	2.5×10^{5}	1.8×10^{1}	3.2×10^{5}
Pu-242	3.76×10^{5}y	1.0×10^{-1}	1.1×10^{2}	3.5×10^{-4}	1.1×10^{2}	1.0×10^{-1}	3.8
Am-241	432y	2.8	5.0×10^{4}	1.8	4.8×10^{4}	9.9×10^{-1}	1.5×10^{3}
Am-242m	152y	2.3×10^{-3}	7.6×10^{1}	2.3×10^{-3}	7.6×10^{1}		
Am-243	7370y	8.8×10^{-4}	9.7×10^{1}	8.8×10^{-4}	9.7×10^{1}		
Cm-244	18.11y	2.5×10^{-2}	1.9×10^{3}	2.5×10^{-2}	1.9×10^{3}		



Note: Ra 226 Short-Lived Daughters (SLD) = Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210

Figure 18.2. Radioactivity in the repository as a function of time after disposal.

Grid Layout For Cavern Vaults In Hard Rock

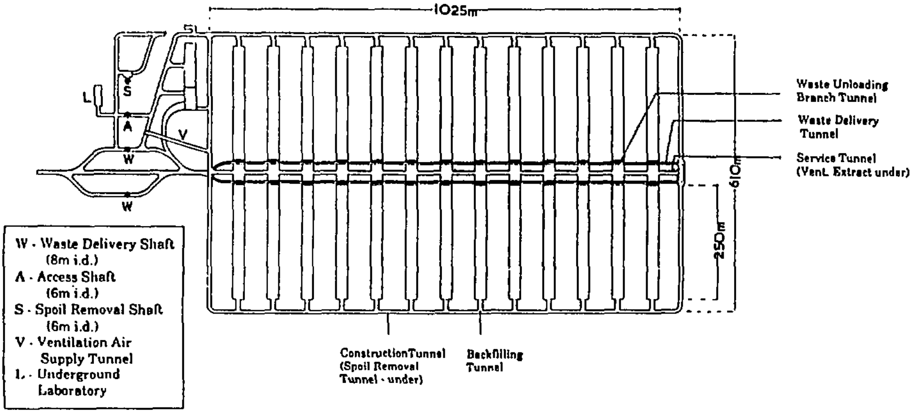


Figure 18.3. Conceptual design of a repository for hard basement rock, showing the disposition of disposal caverns and ancillary works.

very slow towards and under the coast. The lack of any significant head variations in sub-seabed formations will result in almost zero flow.

(c) *Low Permeability Basement Under Sedimentary Cover:* basement rocks of low intrinsic permeability (principally hard shales, mudstones, slates, quartzites or volcaniclastics with some crystalline rocks) occur beneath more recent sedimentary cover. Groundwater movement will occur dominantly in the cover, with little anticipated hydraulic connection with the basement.

(d) *Hard Rocks in Low Relief Terrain:* low relief environments, such as those currently being developed for waste disposal facilities in Sweden, have little driving potential for groundwater movement, although the scale of the groundwater flow systems is small compared with the previous environments, owing to the control by frequent major fracture zones.

(e) *Small Islands:* almost regardless of rock-type. A repository might be sited below the seawater to freshwater interface, where groundwater fluxes are thought to be extremely low. Island environments have the additional advantage of the massive dilution capacity of the sea in respect of eventual releases of radionuclides.

Figure 18.4 shows where these environments are found in Britain.

Five stratigraphic intervals were considered for environments (a) and (b): Kimmeridge Clay (including the Upper Corallian and Ampthill Clay), Oxford Clay, Lias, Mercia Mudstone Group (including the Penarth Group) and the complete Permian sequence including the basal clastic sediments. These formations were selected because their lithologies are mainly argillaceous or evaporitic. Areas of interest have been defined for each interval using boundaries which are the vertical projections to the surface of the following structural contours:

(1) Where any part of the formation is more than 200 m below the surface

(2) Where the base of the formation is 1,000 m below the surface

(3) Where the formation thins to less than 50 or 100 m in thickness, depending on the formation.

Much of the southern and eastern portions of England contain potentially suitable disposal environments. The area known as the Eastern England Shelf, contains all the stratigraphic intervals considered. Here the geological complexity is minimized by the absence of significant faulting and folding.

The 'basement under sedimentary cover' environment (c) is represented by a large area of Precambrian and Palaeozoic basement present at relatively shallow depths as part of the London Platform. This is covered by up to several hundred meters of Mesozoic sediments. The boundaries of the area of interest were initially defined such that the basement was not overlain by any significant aquifer, but were subsequently revised when it was appreciated that this may not be a critical safety issue.

Low-relief crystalline, igneous and metamorphic rocks, well indurated argillaceous rocks and some clastic sediments (d) are found mainly in the north and west of Britain. They do not occur in England, and in Wales are only found in Anglesey and the Lleyn Peninsula. In Scotland such areas are mainly restricted to the east and northeast, and to parts of the west coast and the Outer Hebrides. The geology of these areas varies considerably from peneplained Lewisian gneiss, through granites intruded into Moine metasediments to extremely thick, highly indurated sandstones.

More than one hundred small islands (e) with areas greater than 0.5 km^2 were identified. Those with extreme topography and those not sufficiently far from the shore to have independent hydrogeological regimes were not included. The majority of the islands lie on the west coast of Scotland, or in the Orkneys and Shetlands, although a few are found around the coasts of England and Wales.

Since these five geological environments cover such a large part of the UK it was considered reasonable to try to reduce the initial 'area of search' by concentrating at the outset on areas where the geological structure and predictability were simplest. The environments were thus grouped with respect to their relative geological complexities and the consequent degree of difficulty thought likely to be encountered in both investigating and assessing them:

(1) Types d, e, and b (in areas of low geological complexity),

(2) Type a and b (in areas of greater geological complexity), and

(3) Type c.

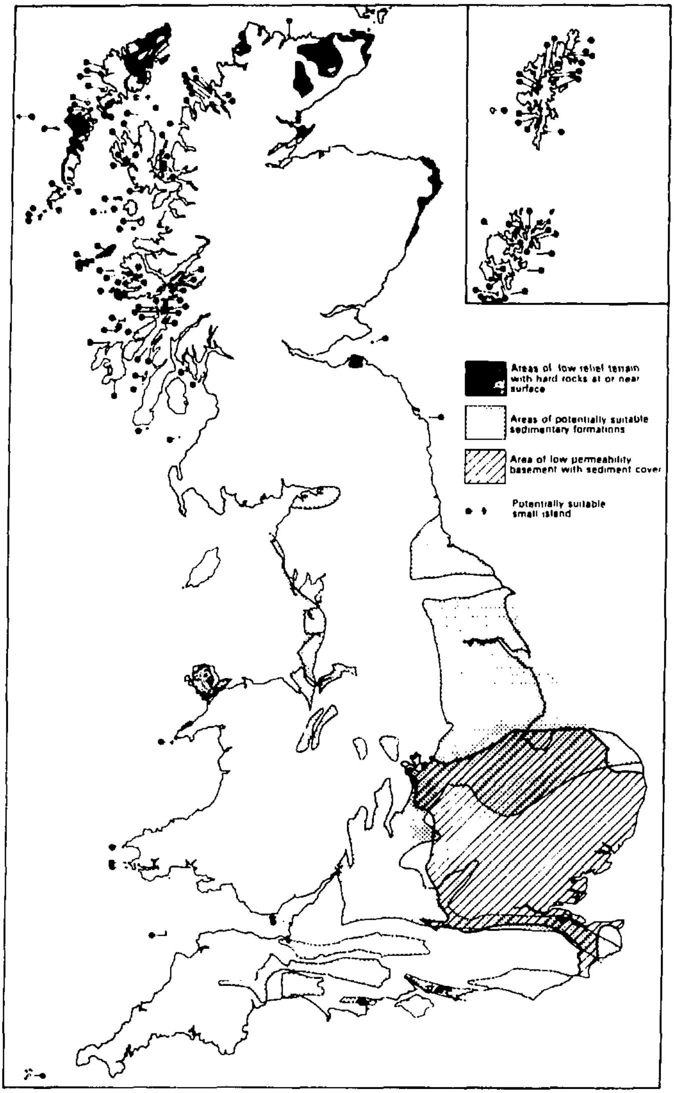


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Figure 18.4. Geological environments in Britain considered to have potential for deep repository development.

It was decided to investigate the potential of Group 1 first; hard fractured rocks in low relief terrains, small islands and offshore dipping sediments in areas of simple structure only. The safety assessment modelling teams felt that the basement under sedimentary cover environment (Group 3) offered such potential that it too was investigated from the start, regardless of potential complexities. It was also considered to be conceptually quite different, and consequently important to assess in more detail. Two additional 'offshore' concepts were included at this stage; disposal beneath the continental shelf in either hard, fractured basement rocks (mainly beneath the Atlantic Ocean around the north-west of Scotland), or in the seaward dipping sediments beneath the North Sea. Both concepts involved gaining access to a repository via an oil-platform type structure. In the hard basement rocks, the repository would be little different in form to one situated below the land, but for the sediments, a matrix of wide shafts was proposed to contain the waste.

Reducing the still considerable area of search on the UK mainland down to a shortlist of sites involved applying a variety of non-geological factors to the assessment both of areas, and the initial list of several hundred potentially available sites in those areas. Planning and non-radiological environmental impact considerations had an immediate effect in considerably reducing the geological area of interest (Figure 18.5), and matters such as the size and shape of sites further reduced the list. Following this initial sifting, the iterative process of arriving at a shortlist of about ten sites eventually made use of a multi-attribute decision analysis system very similar to that already demonstrated in the choice of sites for disposal of high-level waste in the USA (Keeney, 1987; Merkhofer and Keeney, 1987). Further attributes considered covered issues such as post-closure radiological safety, safety and costs of transport of wastes to the repository, overall costs, operational safety of various repository designs, and the many facets of local and national impacts.

The geological input to this model involved assessing sites in terms of their predictability (basically, how simple it would prove to characterize them adequately, and answer the most probable critical questions arising from the safety assessment) and the availability of proven techniques to obtain the relevant data in the rock types and environments concerned. The latter factor obviously militated against the offshore concepts, where detailed characterization would be both difficult and expensive. Additional geological input was incorporated in attributes dealing with construction costs and the general 'robustness' of a concept; essentially reflecting the level of confidence in being able to develop and operate a repository in a particular environment using current well-tested technology. Again, these attributes militated strongly against the offshore concepts in comparison with the land-based alternatives.

When a final shortlist emerged from this analysis, Nirex decided to concentrate its initial field investigations on the two sites with the most "nuclear experience", reserving its investigation of any other shortlisted sites for the event that neither Dounreay nor Sellafield prove suitable.

18.4. The Geology of Dounreay and Sellafield

Both sites now selected for preliminary investigation are on the coast, and both lie on the very edges of sedimentary basins. Consequently both sites are underlain by sediments which display quite rapid thickening towards the basin and the characteristic development of growth faulting parallel to the basin margins, and both have basement rocks within reasonable depths as a target host formation for a waste repository.

Dounreay on the north coast of Scotland, lies close to the western margin of the Orcadian Basin in which the Devonian age Caithness Flagstones were deposited. To the immediate south and east lie the Reay Diorite and the Strath Halladale Granite, which formed part of the eroded mountain complex from which the continental Devonian sediments were formed in the intermontane Orcadian Basin. A cross-section through the site in a northwest-southeast direction (Figure 18.6), based partly on a recent seismic reflection survey, illustrates the general structure in the immediate area of the site. The Strath Halladale Granite crops out 3 km to the south of the site, and is present as an easterly dipping sheet within Moine metasediments, and the Reay Diorite is likely to have a similar form. The Moine is most likely to form the basement directly beneath the site. It consists dominantly of psammite and semi-pelite with local calc-silicate bands and rare quartzites, and may be migmatised.

The site itself is underlain by rocks near the base of the Middle Devonian, Upper Caithness Flagstone Group. These rocks comprise an alternating sequence of calcareous pale grey to greenish-grey siltstones and fine grained sandstones with rarer mudstones, of believed lacustrine origin (Donovan, 1980). They have a characteristic flaggy appearance, are cut by well developed, broadly spaced orthogonal and rhombohedral joint sets and have a regional dip of about 10°. Two divisions of the Caithness Flag-

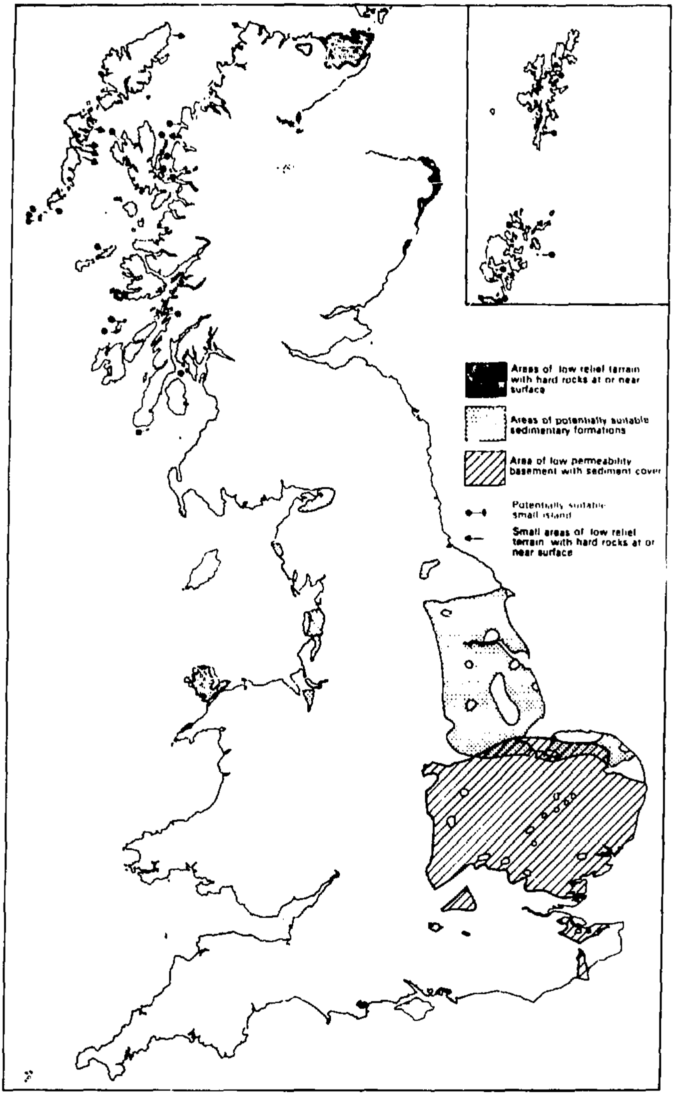

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Figure 18.5. Reduced area of search following geological ranking and superposition of planning and environmental factors.

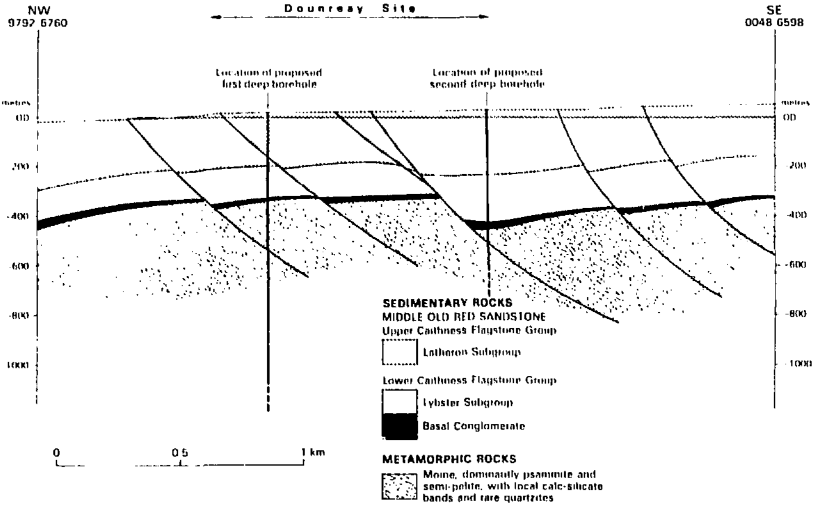


Figure 18.6. Cross-section showing the predicted geology of the Dounreay site.

stones are likely to be present beneath the site, the Latheron Subgroup of the Upper Caithness Flagstone Group overlying the Lybster Subgroup of the Lower Caithness Flagstone Group. There is likely to be a relatively thin basal conglomerate.

Figure 18.6 shows that the sediments are cut by normal faults, throwing down to the east and dipping at 40° to 60°, and exhibiting syndepositional movement. Throws generally decrease upwards, from as much as 130 m at the base of the Devonian to perhaps not more than 10 m at the surface. Small scale reverse faulting can also be seen in coastal exposures. These faults can be traced into the basement where they may coincide with pre-existing shear zones, reactivated during Devonian basin development. The sediments beneath the site in the proposed location for the first deep borehole are approximately 350 m thick, but they thin rapidly towards the west, such that the basement is exposed 1.5 km southeast of the site.

The groundwater flow pattern in the area of the site will be dominated by the location, orientation and properties of the faults, especially where they are present within the basement. The flagstones have relatively high hydraulic conductivities, but the area is of low relief and groundwater heads are expected to be small throughout the formations of interested. The most probable host rock for the repository is the Moine at depths between 700 and 1000 m.

Sellafield lies on the Lake District coastal plain, which is almost completely covered by superficial deposits consisting of a complex admixture of many recent sediment types, up to 55 m thick. A cross section through the site in an east-west direction, based on recent seismic reflection data, illustrates (Figure 18.7) the structural complexity of the region, which lies on the eastern margin of the Irish Sea Basin. The superficial deposits overlie the Ormskirk Sandstone and the St. Bees Sandstone, of Permo-Trias age, which dip at 10° to 15° to the west and southwest and thicken rapidly in the same direction. The St. Bees Sandstone contains more shaley and mudstone partings towards its base, and overlies the St. Bees Shales which are comprised of two principal facies; in the lower part, blocky-weathering siltstone and silty mudstone, commonly gypsiferous and with coarse sandy bands calcareous concretions and, above, laminated micaceous siltstone, mudstone, and subordinate and sandstone with load casts, desiccation cracks and mud-flake breccias. Below the St. Bees Shales is a thick sequence of St. Bees Evaporites containing three cycles. Thick anhydrites may be developed, as may halite, and the lower parts of the St. Bees Evaporites may contain thick-bedded dolomites. The evaporites rest sharply on basal

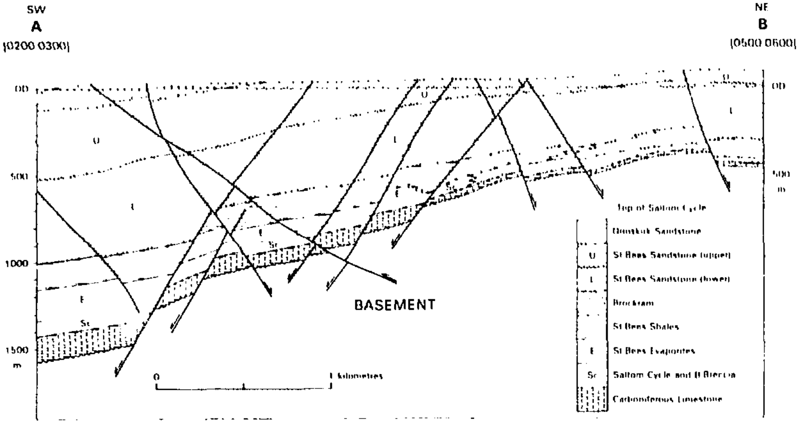


Figure 18.7. Cross-section showing the predicted geology in a north easterly direction from Sellafield.

breccia, which lies on an irregular surface of lower Palaeozoic and Carboniferous age. The base of the Permo-Trias sequence is represented in places in the east of area by Brockram, a marginal conglomerate of the St. Bees Sandstone which, in its lower parts, may be the lateral equivalent of the St. Bees shales and St. Bees Evaporites.

Whilst inland from Sellafield the Lower Palaeozoic basement rocks are predicted to belong exclusively to the Borrowdale Volcanic Group lying unconformably on the Skiddaw Group, beneath and to the west of the site it is thought that Silurian greywackes are more likely to be present. The Borrowdale Volcanic Group is made up of intermediate to acid lavas and pyroclastic rocks, associated sedimentary and volcaniclastic strata, and the Skiddaw Group of slates and greywackes. Both groups are intruded by igneous rocks including, locally, two major granitic bodies, the Eskdale Granite and the Ennerdale Granophyre. Carboniferous limestone lies with a strong unconformity on the basement over parts of the area, and can be as much as 200 m thick. Due east of Sellafield it is not present. Shales and mudstones with evaporites of the Mercia Mudstone Group are present a short distance offshore, and high angle normal and, occasionally, reverse faults are ubiquitous throughout the whole of the area. Three distinct phases of faulting have been recognized, with vertical displacements of up to 250 m.

The basement rocks in the region would allow for repository construction at depths of around 1000 m to the east of Sellafield. They may have suffered two phases of deformation prior to the syn-depositional Permo-Triassic faulting. Groundwater flow takes place dominantly within the St. Bees Sandstone, and is probably directly towards the Sea, being recharged in those regions further inland where the superficial deposits are either thin or absent. The pattern of groundwater flow is likely to be strongly controlled by the faulting, by the large vertical contrasts in hydraulic conductivity caused by the varied composition of the sediments and, in part, by the thickness, hydraulic properties and extent of the superficial deposits which are also present offshore with similar thicknesses to those on land. Flow within the basement will be determined by the extensive fault system which is thought to be present, and by the continuity and properties of the overlying low permeability shales and evaporites.

18.5. The Site Investigation Programme

The programme of site characterization that was just commencing at the time of writing requires planning consents from local and regional authorities at several stages of the work. Obtaining planning consent for the eventual construction of a repository is likely to result in a public inquiry before any significant work can start. The repository will have to be licensed by the national regulatory authorities before it can commence operation. Under present procedures, consent to drill the first exploratory boreholes also requires planning approval from the local authorities.

Current proposals for the investigations of Dounreay and Sellafield envisage a two stage programme of work at each site prior to the selection of one of them. If the anticipated public inquiry is in favour of development at one of the sites, then a third stage of site characterization will commence, in parallel with the progressive construction of the repository.

The first stage of work, currently underway, is a preliminary exercise to provide the designers and the safety assessment teams with a 3-D structural model of the sites. This will be achieved largely by a programme of regional geophysical surveying, supported by the drilling of two deep boreholes (800-1800 m) at each site. These boreholes will be used to calibrate the seismic and gravity surveys, and to provide first information on basic hydrogeological properties of the rocks. Head, flux and transmissivity measurements will be supported by preliminary hydrogeochemical evidence for the residence times of deep groundwaters. The core material will provide data on geotechnical properties for the design team, as well as material for experimental studies of rock/radionuclide interactions.

During this work, which will take about 12-18 months, the safety assessment teams will be constructing refined groundwater flow models both to characterize the sites and eventually, to test their potential response to future perturbations caused by the repository and climatically induced hydraulic fluctuations. This approach will allow very specific questions to be raised for consideration in the second stage of the work. For example, it is envisaged that predictions made by the flow models can be tested by making hydraulic measurements in zones specified as particularly sensitive by the models. The potential significance of various features (such as fault zones, lithological variations, and other heterogeneities) can be tested by the model using estimates of parameter values, before specifying the most useful means of providing supporting field data, and the best locations to make the measurements. The second stage, which will overlap with the first, will thus comprise a longer period of drilling, hydraulic testing and groundwater sampling, continuing until about 1993.

The first stage in developing the repository, which will take place after the public inquiry, will be the sinking of an exploratory shaft, and the commencement of underground exploration via trial adits. The objective of this third stage of work will be to characterize in detail the precise volume of the rock in which the repository will lie, and to allow for a period of experimentation focussed on safety or construction issues, and the demonstration of the technological aspects of waste emplacement. In this stage it will probably be necessary to make detailed changes to repository design or to details of the engineered barrier design in order to accommodate specific features of the rock. It is intended that as much as possible of the exploratory work be conducted from the underground facilities using remote sensing geophysical techniques and, where possible, to ensure that exploratory boreholes are subsequently mined out during construction. This is to minimise damage to the rock surrounding the repository, and avoid significant disruption of the natural groundwater flow system.

18.6. The Geological Issues Arising from Safety Assessments

18.6.1. Assessment Methodology

Performance assessment of a disposal system is an iterative process that guides the design of the repository by defining the most sensitive components and issues, and the physico-chemical processes that are of prime importance to safety. It also highlights areas of critical data uncertainty and so helps to focus site characterization work in common with other national programmes, the assessment models used in the UK tend to be based on conservative assumptions; that is, they take a pessimistic view of future performance and will consequently tend to overestimate the radiological impacts of disposal.

Both Nirex and DOE have developing methodologies for radiological safety assessment which make use of both deterministic analyses, and of probabilistic risk assessment (PRA). With PRA, the overall performance of a repository is calculated using a series of connected models which describe, in a simplified manner, the behavior of critical components or processes in the repository, the geosphere, and the biosphere. The data for these models are in the form of probability distribution functions (PDFs), the estimated or measured frequency of occurrence of all possible values of each parameter. The approach with deterministic assessments is to look at the detailed performance on the whole, or parts, of the system when subject to a variety of evolutionary 'scenarios'. These use best estimates of parameter values and are particularly useful in understanding the impact of an event or process. The results of PRAs, although logically more comprehensive, can be less easy to interpret directly. Consequently, both approaches are required in order to understand future performance, and the impacts of uncertainties in the data used.

A major component of the Nirex site selection exercise was the information arising from a two-stage 'comparative assessment of concepts and areas for deep emplacements: CASCADE (Billington, et al., 1989), which involved modelling the performance of basic repository designs situated in generic geological sites, loosely based on the most promising areas of interest. This work was aimed at assessing how well concepts performed against the yardstick of the assessment principles laid down in 1984 by the Department of the Environment (DOE, 1984). These state that, along other guidelines, the appropriate radiological safety target for a repository, at any time, is a risk to an individual in a year equivalent to that associated with a dose of 0.1 mSv; about one chance in a million.

Prior to the CASCADE exercise, the DOE had been carrying out its own 'dry run' performance assessment exercise for a hypothetical deep repository situated in clays at approximately 400 m below the Harwell site in Oxfordshire. The basic geological information had been provided by some limited exploratory drilling carried out by the British Geological survey in 1980-81 (Black, et al., 1985). All lithological and hydrogeological data were taken from a group of very closely spaced boreholes, together with some regional spring and well sampling in the recharge area of some of the aquifers penetrated. Consequently the data were considerably limited compared to what would be expected from a real site investigation. The results of this modelling exercise (Gralewski, et al., 1987) highlighted the need for regional data, rather than information only from the site itself, and pointed to the importance of understanding groundwater flow at a site using 3-D as well as 2-D hydraulic models. Even with 2-D models it was possible to show the potential significance to radionuclide releases to the biosphere of multiple return pathways through the rocks. Although neither the Dounreay nor the Sellafield sites possess the same type of alternating aquifer/aquitard lithology as Harwell, these results are equally valid. Both sites will require 'off-site' drilling, and both will require 3-D modelling to fit together a picture of possible radionuclide migration paths in a complex interconnected network of major fracture zones and lithological boundaries. 3-D Modelling is thus a complex exercise which is most useful for developing a working understanding of a site whereas, for more straightforward illustration of the results of certain process or options 2-D, and even 1-D, radionuclide transport models are often most appropriate.

From the above examples there are clearly many issues related to the geological input to safety assessments that could be selected for discussion. However, a number of extremely important points have emerged from both the CASCADE study and the parallel research Programmes of both Nirex and the DOE, and are currently acting as the focus of interest. These are highlighted in the following sections.

18.6.2. Groundwater Flow Modeling and the Problem of Geological 'Probability Distribution Functions'

The importance of being able to predict groundwater residence and transit times is made clear in all the British assessment work to date. Much interesting discussion has taken place on the topic of selecting values for critical parameters such as hydraulic conductivity for application to the porous-medium flow models which will almost inevitably be used for regional scale groundwater flow models in all types of rock. This has been focussed by probabilistic models, which demand PDFs for such a parameter. While it is quite possible to give estimates of upper and lower bounds of, for example, fractured rock hydraulic conductivities, application of the extreme values to very large columns of the rock mass when making steady state predictions of flow can produce very short apparent return times that are inconsistent with our perception of real flow regimes where any relatively rapid movements are restricted to very discrete zones. This issue, together with others related to flow in fractured rocks, is being investigated through UK involvement in projects such as the Stripa test mine in Sweden. The best resolution will always be found when flow models are applied to real sites, where there is some constraint on flow predictions provided by detailed hydraulic testing and hydrochemical evidence of groundwater residence times. This was certainly a valuable experience found during the Nirex shallow site investigations in 1987 (e.g. Bath et al., 1988). For the time being, however, despite the overall very conservative approach taken in safety assessment, we believe that it would be unwise to place too much emphasis on the extreme results of generic flow models.

The lack of well-documented databases for many geological processes with observations over adequate time periods makes the interpretation of the results of PRAs that use PDFs to attempt predictions over millions of years difficult. Risk analysis works properly when the models used are well validated, and the PDFs have been obtained by extensive testing and observation of materials in use. One might consider, for example, the stress-strain behavior of engineered components using in the construction industry. Prediction over geological timescales shares the same problems as very long-term global climate prediction; most processes occur very slowly, or events occur very irregularly with long periodicity and frequently go unobserved. We only infer their nature by their effects. While geologists can generate valid PDFs for some geological parameters, it is important to be quite clear how, exactly, the data are going to be used. For example, the expense and effort of obtaining fracture densities and apertures across a whole site could be enormous and may be quite unnecessary for the type of modelling which might be most appropriate. For other data it may not be possible to gather them at all, and the uncertainties may be irreducible. For these, the alternative is to set the PDF bounds very wide indeed. This can produce very pessimistic results or, in some cases, optimistic results in which the 'expectation values' of risk are reduced owing to the wide spread of input parameter values. PRAs of very long term geological behavior, although very useful in developing understanding, should be treated with great caution if decisions are to be based on their quantitative results.

18.6.3. Time Dependency of Natural Processes

In the UK, major disruptive geological events are unlikely to disturb a repository to a significant extent, owing to the predicted large-scale tectonic stability of the British Isles for the coming 10^8 years. However, even on the one million year timescale, climatic change is likely to have a considerable effect, not only on the biosphere, where the recipients of any future radiation doses could be living in anything from a 'greenhouse effect' super-interglacial to a full glaciation, but also on the geosphere, where groundwater fluxes could be substantially modified.

When considering the effects of climatic change in Britain, the principal geological features of concern are the changes in sea-level and drainage that could occur, together with erosion rates and the stress and hydraulic response of the rock to ice-loading and unloading. Safety assessments show the benefits of having a repository under the sea bed or on a small island in order to take credit for the massive dilution potential of the oceans for any eventual releases. This was taken into account in defining hydrogeological environments in the UK in which to seek repository sites, and both Dounreay and Sellafield are, indeed, on the coast. However, studies of climatic change suggest that the current sea-level in Britain is relatively very high, that beyond about 10,000 years into the future periglacial conditions are likely to dominate for 70% of the next million years, and that sea-levels will consequently fall by perhaps 70-140 m. The topographic consequences of this can be seen in Figure 18.8 which demonstrates that many current coastal and island locations could be far removed from a marine environment.

The central issue with respect to time dependent processes is not so much the ability to model what occurs at any particular 'snapshot' in time, as the problem of how to cope with their cumulative effects, particularly when a process is cyclical with a relatively short periodicity (say of the order of 10,000 years). In some areas this is probably not a significant concern; for example, hydrochemical evidence suggests that in both thick sequences of sediments and in some deep fractured rock environments, the response time of fluxes in the deep groundwater regime to transients in hydraulic head and recharge water chemistry as a result of sea-level changes, is extremely long (Neuzil, 1986). The recovery time of the saline/freshwater interface beneath a small island in hard fractured rock when returned to a mainland environment by a drop in sea level has been estimated to be of the order of tens of thousands of years. These observations do not, however, justify the unqualified application of steady state flow conditions to times beyond about 10^5 years and, in fracture zones in the upper few hundred meters of the UK sites, steady state models are unlikely to be valid on still shorter timescales. Indeed, it may be useful to uncouple the sluggishly responsive zones of the deep groundwater regime from the rapidly cycling regions both at depth and near the surface when considering the estimation and significance of radionuclide concentrations and radiation doses. This means that considerable thought has to go into interpreting dose or risk versus time graphs at extreme times into the future. Much thought is going into the issue of time dependency in both the DOE and Nirex research programmes, and this also has an important input into the topic of time-frames in which to consider the results of performance assessment. This is discussed further below.

During the course of the future site investigations it is anticipated that much useful information on time dependent processes will arise from palaeo-hydrogeological studies of the sites con-

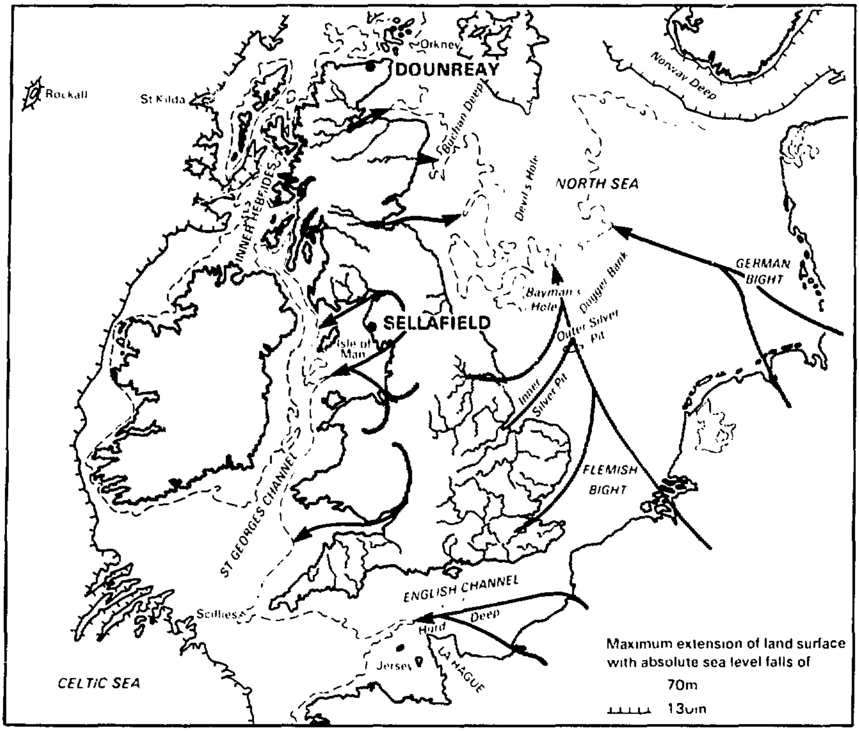


Figure 18.8. Extension of land surface in Britain in periglacial conditions.

cerned, combined with studies of the effect of cyclical climatic change on the properties of specific conductive fracture zones.

18.6.4. Is Reversible Sorption a Geologically Reasonable Concept?

The simplest models of radionuclide transport in advecting groundwater make use of laboratory derived distribution coefficients which describe the uptake of radionuclides from the water onto rock surfaces by a variety of processes commonly termed 'sorption'. These coefficients vary with the physical and chemical state of the water, the radionuclide, and the rock surface and there is always some uncertainty in selecting ranges of values in geological environments which are inevitably spatially and temporally inhomogeneous. A complimentary issue is the very long time periods treated in groundwater transport calculations. Laboratory sorption kinetics appear to be very fast initially, and settle down to an apparently steady state in a matter of hours. Sorption is taken to be reversible. It is difficult to believe that this reversibility persists over geological timescales, and that second or third order kinetic processes do not lead to irreversible fixation within the surfaces of minerals. Where this could be shown to be the case, by studies of naturally occurring radionuclides for example, then a sorption model is clearly giving faster radionuclide transport times (i.e. the safety case is making a generally pessimistic assumption).

The alternative approach is to use our knowledge of the solution chemistry of the radionuclides and components of the mineral phases in the rocks to produce purely thermodynamic models of radionuclide/rock interaction in which the effects of physicochemical changes can, in theory, be predicted. The problem here is that many of the chemical species which might exist are exotic, and thermodynamic data are only slowly becoming available. As with sorption, this approach is also unable to address comprehensively the kinetics of radionuclide/rock interactions over very long timescales, when reactions take place in aqueous pore and micro-fracture environments where diffusion, structured water layers, and complex mineral surface electrochemistry may dominate transfer processes, with consequent effects on the stability of radionuclide complexes. in some deep geological environments only metastable equilibria appear to exist between porewaters and rock, despite the age of the rock formation, and these are difficult to model.

The thermodynamic approach does come closest to reality, and current research is enhancing the databases used considerably. In the meantime, for assessment purposes, reversible sorption remains a usefully conservative assumption, despite the fact that we are unconvinced that it can always maintain reversibility over very long timescales. The issue is that of defining under what circumstances conversion to an irreversible fixation mechanism occurs in the rock formations of concern in order to allow the safety assessments to be less pessimistic and more realistic. There is clearly much that could be learned from more detailed studies of natural systems.

18.6.5. Gas Release and Migration from the Repository

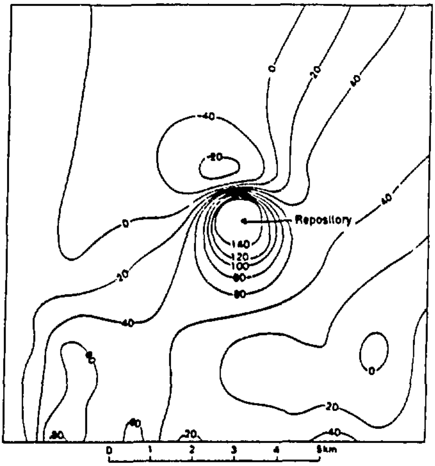
Gas is produced in the repository during the degradation of the waste and its containers. A wide variety of gaseous species will result from the biodegradation of some of the wastes during the first hundred years or so, although the principal product will be carbon dioxide. However, the main source of gas is likely to be the production of hydrogen during the aerobic corrosion of aluminum and magnox in ILW and, more importantly, the anaerobic corrosion of steel in both LLW/ILW. This hydrogen production is likely to be significant during the first few hundreds or thousands of years after disposal, with a potential production rate of about two million cubic meters/year (at STP) during the first 500 years (Rees and Rodwell, 1988). Were the repository completely gas-tight this could lead to disruption of the engineered barriers, and even the rock, by overpressure. However, it is expected that the gas will be able to escape relatively easily through the fracture network in the rock. The effect of this progressive gas release on radionuclide transport and groundwater flow is currently being assessed, and models are being developed for two-phase flow in fracture networks. These are being tested by experiments in boreholes to measure the rate of pressure dissipation after gas injection into deep, fractured rock.

18.6.6. Human Intrusion into the Repository

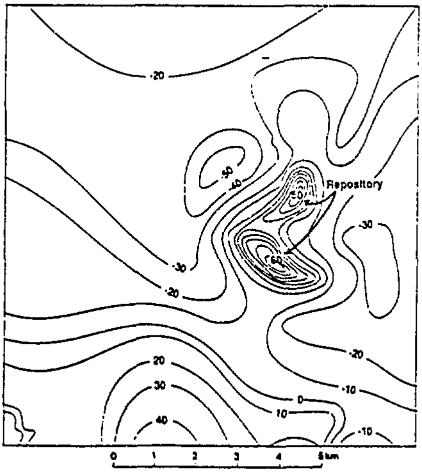
Perhaps the least predictable and most philosophical aspect of safety assessments is the treatment of future unintentional intrusion into a lost and forgotten repository during drilling or mining. In the UK attempts are being made to address this issue in as scientific a manner as possible, largely because early assessments indicated that such activities could constitute one of the principal release mechanisms. The main risk is seen to arise to a geotechnical worker who handles contaminated core material from a borehole through or close to a repository. Consequently the question arises as to the probability of such drilling taking place.

It has been a relatively simple matter to relate past drilling practice and frequency to the type of rock formation in which a site lies, and so produce an annual frequency of borehole intrusion in terms of holes/year/km^2. In the sites of interest, such drilling has been either for water or mineral exploration. Such an approach makes some very fundamental assumptions about unchanging exploration drilling, and mineral or hydrocarbon extraction techniques. In particular, the basic assumption of total loss of all records of a repository, which makes such intrusion inevitable when very long periods are considered, raises many questions about the future nature of society and the way in which the results of safety assessments should be interpreted.

Work has thus been carried out to put exploratory drilling into the wider context of how exploration programmes work at present. In particular, interest is being shown in the type of remotely sensed geophysical anomaly that might be presented by a repository, and whether this would alert any inadvertent intruders to potential danger. Figure 18.9 shows the calculated magnetic anomaly that would be produced by a waste repository at Dounreay containing about 3 million tons of iron in the waste and engineered barriers, and an even more distinctive anomaly for a repository in a deep clay formation. The apparent man-made regularity of these features and their persistence (even following corrosion of steel, the green magnetite resulting from the anaerobic process remains ferromagnetic) may, however, attract as much as deter future prospectors. An analysis of the likely risks from human 'intrusion' for a repository situated in the geological environment discussed earlier has been made by



(a) Dounreay: Combined regional and modelled anomaly.



(b) Clay site: Combined regional and modelled anomaly.

Figure 18.9. Magnetic anomalies produced by repositories at Dounreay and at a national site in eastern UK. The repository at Dounreay is assumed to be that shown in Figure 18.3, whilst the repository in clay is in the shape of a V. Further data on these calculations are given in Jowett and Chapman (1989) (contours in nT).

Nirex (Jowett and Chapman, 1989). This indicated the risks to be comparatively lower at sites such as Dounreay and Sellafield than in the sedimentary rocks of Eastern England. Although geologists can contribute much to this debate, its final resolution will depend largely on the perceptions and attitudes of current generations towards the significance of risks to unknown future societies.

18.6.7. Long-term Excavation Response of the Rock

It is generally recognised that the construction of the repository may significantly influence the hydraulic conditions in the host rock and surrounding formations. For this reason, as well as to model the effect of stresses on regional groundwater flow, it will be important to characterize the in-situ stress regimes during site investigations. Excavation response around openings in the Moine metasediments and Borrowdale Volcanic Group rocks at Dounreay and Sellafield will depend on the excavation method and on the stress distribution in the rock mass during and after excavation. The disturbances of interest are the creation, extension or reactivation of fractures that could result in either a modified structural condition, or modify the hydraulic conductivity of the rock close to cavern and shaft walls. This could result in short-circuiting of hydraulically active zones in the rock along 'skin' regions of enhanced conductivity, which, if significant, would require special grouting and sealing techniques to be employed during construction. Again, UK involvement in the Stripa mine research is providing valuable information on such techniques.

A further issue of concern is the very long-term response of the rock to the presence of voids in the repository. Although it is the intention to backfill the whole repository completely, cavern crowns are very difficult to fill totally, and are the zones to which any growth in voidage in the wastes owing to corrosion and degradation would eventually migrate. Although stoping of such voidage upwards into the overlying rock is considered unlikely from preliminary assessments by Nirex, the long-term mechanical and hydraulic behavior of such features will need further study when access to the potential repository rock is available during detailed underground investigations.

An additional excavation response which must be accounted for is the de-watering of overlying rock during pumping to keep the repository dry during a 50 year operational life. From the viewpoint of establishing stable geochemical conditions in the engineered barriers, it would be beneficial if the resaturation time after completion of the repository were short, and that any air in the partially saturated rocks dissipated or was consumed by oxidation reactions quickly in order to minimize the aerobic period. Modelling of the effects of various modes of resaturation has been an important aspect of the UK programme of research into corrosion and engineered barrier design, and both resaturation time and re-establishment of reducing conditions are estimated to be of the order of a few tens to a few hundreds of years.

18.6.8. Time Frames for Performance Assessment

The DOE assessment principles indicate that the individual risk target is appropriate at any time. This could be interpreted to mean that individual risk ought to be calculable at all future times. At present, whilst DOE awaits a submission from Nirex which they can assess, the exact nature of what the safety case should contain in terms of protected long-term risks remains a rather grey area. Consequently there is a continuing debate underway on the possibility of using various time frames for performance assessment, and on the type of calculations that might be most appropriate for them. Geological advice is very likely to be at the basis of these discussions, particularly in respect of the longest time-frames being considered.

In our view, the confidence that safety assessment teams can place in the numerical results of calculations of performance at long times into the future does not permit the presentation of very specific figures such as risk to individuals. This view is based, first of all, on the reasons given in the prior discussion of time dependency and cyclicity of natural processes in the shallow geosphere and biosphere. Second, as with human intrusion, the exact meaning of risks and doses to populations and individuals that may or may not exist in the future seems very philosophical. Geologists are required to provide evidence of the longevity of the radionuclide transport and retardation processes being modelled by means of data from geochemical analogues in rock formations. These 'natural analogues' (see, for example, Côme and Chapman, 1985, 1986, 1988), tend to reinforce the view: given earlier that we can uncouple deep processes which are only slowly affected by global environmental change, from processes in the upper tens or hundreds of meters, which respond as readily as the biosphere to such changes. The case is often made that we should not consider individual doses to humans calculated beyond the next ice age (say 10,000 years hence). We would certainly support the view that any quantitative radiological predictions which require more than the very simplest of assumptions about the biosphere/geosphere interface zone after unknown cycles of environmental change, have little real meaning. Consequently, a requirement to present, with a high level of confidence, radiation dose calculations, or risk figures, for times beyond a few thousands of years would seem to place an unreasonable burden of credibility on safety assessment groups. Conversely, our understanding of deep groundwater flow systems suggests that it is quite reasonable to make quantitative predictions about the likely dispersion and disposition of radionuclides throughout the rocks around a repository for very much longer periods.

The question thus arises as to whether alternative comparisons could be useful when considering the acceptability of a waste repository in terms of its very long term 'geological timescale' impacts. In seeking appropriate yardsticks we suggest that, although a dose/risk target is unreasonable for times beyond a few thousands of years, a comparator might be adopted for longer periods that relates the "availability" (location, chemical form, mobility, concentration and fixation) of waste radionuclides to other radioactive or toxic species naturally dispersed through the rock volume. Assessment of such "availability" might, for example, consider the rates at which such species are naturally released to the environment by erosion or mobilization in groundwater. In other words, while targets based on radiological protection may be reasonable for as long as we can reasonably predict how radiation doses might be received, the assessment of longer term behavior might be related to our more justifiable confidence in predicting the nature of the deep geological environment over such timescales.

18.6.9. Validation of Predictive Geological Models

The strand that connects all the issues discussed above is that of using geological knowledge and observations to construct models of the physical processes that affect repository performance, and then using these models to predict future behavior for very long periods. Perhaps the overriding issue at present is whether the predictive models used in performance assessment can be validated. Does the model provide a reasonable representation of reality, and is the representation valid for the time periods for which the model is making predictions?

Much effort is being put into model validation, not only by DOE and Nirex, but throughout the international community. The INTRAVAL project, organised by the Swedish Nuclear Power Inspectorate (Andersson, 1988), and in which both DOE and Nirex take part, is a quantitative attempt to validate radionuclide transport models. The current consensus of this group is that it will take a combination of many types of guidance, laboratory and field experiments, site characterization and natural analogue studies to provide convincing proof that our models and computer codes provide a fair representation of reality. A developing view within INTRAVAL is that it is difficult to validate any geochemical transport model for general use. A model can only really be considered to have been demonstrated as either a valid description of a process, or as a valid description of the effects of a group of processes at a specific site. The former 'process validation' can be achieved largely by field or laboratory experiment, whereas the latter 'site validity' is likely to rely on natural geochemical analogues of multiple processes, or on a thorough geological characterization of the site based on palaeo-hydrogeological interpretation of the evolution of the groundwater regime.

18.7. Conclusions and Prospects

In Britain geologists have been preparing to carry out a thorough site characterization programme for a deep waste repository for the last ten years, during which time much intellectual concept and model development has taken place, but little field testing. In this paper we have been able to focus our previous assessments of the 'state of the art' in the techniques of site characterization (e.g. Chapman, et al., 1987) onto the likely requirements at two specific sites.

In our view geologists now have the techniques and methodologies available to measure the parameters that are likely to be required in repository design and safety assessment. While there is still a lot to be learned about how to apply these techniques most effectively during site characterization, almost all the critical issues to have emerged from recent performance assessment work are largely unconnected with either the data or the data gathering process. By looking at the results of recent research and safety assessments we have highlighted some more general geological issues which go beyond the confines simply of technique. The majority of the issues discussed above are, in fact, concerned with:

(1) The considerable pessimism built into some assessment models as a response to data or conceptual uncertainties (such as how best to use information on hydraulic properties or sorption in models)

(2) Demonstrating confidence in predictions made for processes that occur over 'geological timescales' into the future

(3) How geological data can be used to compare the behavior of natural radioactivity to that mobilised from a repository at very long times into the future as an alternative to making dose or risk calculations for these 'geological' timescales.

In all these areas geology still appears to hold the key to the future.

18.8. Acknowledgements

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Chapter 19

Site Characterization Activities to Investigate Major Geologic Uncertainties at the Potential High-Level Radioactive Waste Repository, Yucca Mountain, Nevada

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In 1957, the National Academy of Sciences-National Research Council (NAS-NRC) recommended development of a mined geologic disposal system to fulfill the objective of permanent disposal of spent nuclear fuel and high-level radioactive waste in a manner that adequately protected public health and safety and the environment (NAS-NRC, 1957). This recommendation included unprecedented technical requirements that would have to be met.

Site selection was initiated and a nationwide screening process began to evaluate various geologic rock types (salt, rocks, crystalline rocks). Prior land use was a factor and led to evaluations of basalt at the Hanford Reservation and of tuff at Yucca Mountain. In 1982 Congress assigned responsibility to the Department of Energy (DOE) to develop a disposal system for spent nuclear fuel and high-level radioactive waste that included interim storage and transportation. The Nuclear Waste Policy Act of 1982 (NWPA) established the Office of Civilian Radioactive Waste Management (OCRWM) within DOE to oversee and manage this congressional mandate (NWPA, 1983). By May 1986, DOE had narrowed the search to three candidate sites (Hanford in the State of Washington, Deaf Smith County in the State of Texas, and Yucca Mountain in the State of Nevada) (DOE, 1986a and 1986b).

In December 1987 Congress enacted the Nuclear Waste Policy Amendments Act (NWPAA) which redirected the Program (NWPAA, 1987). The NWPAA redirected DOE to characterize only the Yucca Mountain site, close out activities at Hanford and Deaf Smith County, terminate efforts to investigate crystalline rocks as a repository host rock, and to discontinue efforts to site a second repository. In order to comply with NWPAA, the Nuclear Regulatory Commission (NRC) siting guidelines (10 CFR Part 60, 1988), and the Environmental Protection Agency standard (40 CFR Part 191, 1985), the DOE must demonstrate the capability of a disposal system to isolate high-level radioactive waste from the accessible environment for 10,000 years. To achieve this goal, a multiple barrier approach will be relied upon. Engineered barriers consisting of the waste-form and waste package must contain the radionuclides for 300 to 1,000 years and the natural geologic setting must provide containment for a 10,000 year period. Emphases for achieving the Program's goal are placed on the natural barriers (geologic, hydrologic and geochemical conditions) which will be evaluated by the site characterization program.

Site characterization includes the activities conducted to gather information about the "geologic" conditions at the site and to evaluate the site's suitability for a repository. This is a process set forth in the NWPA of 1982 that leads to the submittal to the NRC of a license application to construct and operate a repository. The DOE/Headquarters role is to manage the program and provide guidance on policy and technical direction to the Program Participants. Program Participants, under the management of the Yucca Mountain Project Office (YMPO), conduct the technical, scientific and engineering studies necessary to characterize the site. The U. S. Geological Survey (USGS) is responsible for the geologic and hydrologic scientific investigations; Sandia National Laboratories (SNL) is responsible for designing the exploratory shaft, repository, and central surface facilities and equipment, and to conduct performance assessments; Los Alamos National Laboratory (LANL) is primarily responsible for geochemical and volcanism investigations and exploratory shaft test implementation; and Lawrence Livermore National Laboratory (LLNL) is responsible for the waste package scientific investigations related to design and testing. Prior to collecting data or conducting site characterization, each Program Participant must have a qualified Quality Assurance (QA) program in place.

The objectives of site characterization are scientific investigations to establish the geologic, hydrologic, and geochemical conditions at the candidate site and provide the data needed for design of the waste package and the repository, including the Exploratory Shaft Facility (ESF), and to provide the necessary data for performance assessment calculations of the repository system. Data collected during site characterization will be used to evaluate site suitability and to support the recommendation to license the repository if the site is found suitable. Funds for site characterization are provided from the Nuclear Waste Fund which collects fees (1 mill/kilowatt of nuclear generated electricity) assessed to the utilities that operate nuclear power plants.

The site characterization program is described in the Site Characterization Plan (SCP) (DOE, 1988) which is a comprehensive initial plan required by the NWPA of 1982 and the NRC regulation 10 CFR Part 60. The SCP presents the overall rationale for the site characterization program and is the initial comprehensive scientific investigation plan for conducting site characterization at Yucca Mountain. Information needed from site characterization, as determined by a systematic analysis of regulatory requirements, is identified in the SCP. The SCP discusses overall testing strategy and describes the hierarchy of programs, scientific investigations, studies and activities to be conducted in order to provide the needed information. The document contains over 6,000 pages; chapters 1 through 5 describe the current understanding of the site; chapters 6 and 7 describe the conceptual repository and waste package designs; and chapter 8, which is the majority of the document, describes the site characterization program. The SCP underwent extensive reviews by the DOE and Program Participants before it was published and was commented on by the NRC, State of Nevada, other oversight groups, and the general public after issuance.

The Site Characterization Plan is the basis for study plans. Study plans define the scientific investigations that will be performed by the Program Participants. A total of 106 study plans, covering surface-based testing, underground testing, laboratory studies, and syntheses and modeling studies, are scheduled to be developed. Study plans provide more detail on each study described in the SCP, including information on activities, tests and analyses, methods and procedures, duration and sequencing of activities, constraints, and QA requirements. Study plans undergo a rigorous, QA controlled, review process before any new investigation can begin.

The site characterization program is designed to provide information needed to establish characteristics of phenomenological processes and to establish site conditions, including spatial and temporal trends and variability. The program has two major components: surface-based testing, to investigate previously recognized features and structures, and to provide systematic coverage of the site and surrounding areas to establish trends and overall variability of site conditions; and underground testing, consisting of in situ testing and other underground investigations to improve the understanding of phenomenological processes and sub-surface site conditions. The DOE's confidence that the database obtained through site characterization will be "appropriate and adequate" for site suitability, design, performance assessments and licensing will be increased by:

(1) collecting data to evaluate the values of basic parameters at locations through the site;

(2) analyzing statistical variability of values for basic parameters;

(3) developing the capability to describe/predict trends in site parameters using the best available models;

(4) obtaining values for the parameters needed to evaluate alternative conceptual models;

(5) establishing the range of parameter values for input to performance assessment models; and

(6) iterative evaluation of adequacy to support design and performance assessment needs.

The site characterization program is flexible and can be modified as data are collected or additional information needs are identified.

Yucca Mountain is located in the Amargosa Desert of the southwestern United States approximately 160 kilometers northwest of Las Vegas, Nevada, in a region with sparse or no population. The land is owned or managed by three Federal entities consisting of the DOE, the United States Air Force (USAF), and the United States Bureau of Land Management (BLM) (Figure 19.1). The Yucca Mountain site is located adjacent to and encompasses a small part of the Nevada Test site (NTS) where DOE conducts underground nuclear tests. The site is situated in the northwest-trending Walker Lane tectonic zone, a broad zone of deformation that extends from northeastern California to southern Nevada, and is expressed by large-scale right-lateral strike-slip faulting. Basin and Range block faulting, strike-slip faulting, localized faulting related to caldera formation, and possibly detachment faulting, typify the regional structural style in the vicinity of the proposed site. More locally, north-trending structural blocks have been tilted eastward by high-angle west-dipping normal faults (Figure 19.2) (Scott and Bonk, 1984). The major suspected Quaternary faults near the proposed site include the Bow Ridge, Ghost Dance, and Solitario Canyon faults.

The proposed site is also located in the Death Valley-Pancake Range volcanic zone which is typified by scattered basalt centers overlying Tertiary rhyolitic ash-flow tuffs (Crowe et al. , 1983). The rhyolitic volcanic tuffs comprising Yucca Mountain were erupted primarily from the Timber Mountain-Oasis Valley caldera complex, between 16 to 9.5 million years ago. The proposed repository horizon is in the densely welded, devitrified zone of the Topopah Springs Member of the Miocene Paintbrush Tuff. The Topopah Springs Member was chosen because of its thickness, lateral continuity, dense welding, and its location in the unsaturated zone. The proposed repository horizon would be located in the unsaturated zone approximately 300 meters above the water table and 365 meters beneath the eastern flank of Yucca Mountain.

Younger Pleistocene basaltic volcanism has occurred in isolated areas immediately to the south and west of Yucca Mountain. The Lathrop Wells basaltic cinder cone is approximately 25 kilometers south of the proposed repository and may have erupted as recently as 15,000 to 25,000 years ago. The last eruptive event of Red Cone and Black Cone, located west of the site in Crater Flat, was approximately 1.2 million years ago. Drilling of geophysical anomalies, geochronology, field studies, and geochemical analysis of scoria sequences will be used to evaluate these and other volcanic features to determine the potential for future activity.

At this point in time there are several major uncertainties concerning the natural conditions at Yucca Mountain that must be satisfactorily characterized and understood to determine whether or not the proposed site is suitable as a high-level radioactive waste repository. One of the major, and perhaps most critical, sources of uncertainty is the geohydrology of Yucca Mountain; flow paths and hydrologic processes in the unsaturated zone must be determined. Tectonic conditions are another source of uncertainty; surface faulting and ground motion prior to closure of the proposed repository, the impact of tectonics on hydrologic conditions after repository closure, and the potential for volcanism will have to be evaluated.

Reducing the uncertainties associated with the geohydrologic system at the site, and in particular with the unsaturated zone, are critical to site characterization. The flow mechanism in the unsaturated zone needs to be determined. If the predominant mechanism of flow is through a network of fractures, then groundwater travel time from the proposed repository to the accessible environment could be less than ten thousand years, whereas if the flow mechanism is through the rock matrix, then groundwater travel time to the accessible environment could be as long as tens of thousands of years (Sinnock et al., 1986). The rate and areal distribution of net infiltration near the ground surface must also be determined, as must the rate and direction of ground-water movement in the unsaturated zone from the ground surface to the repository horizon, and from the repository horizon to the saturated zone, and ultimately to the accessible environment. Other uncertainties about the hydrology of Yucca Mountain that need to be addressed are whether or not there is a significant component of lateral flow in the unsaturated zone, and whether or not there are occurrences of perched water at the site.

To reduce the uncertainties of the unsaturated zone, and to better understand the site specific and regional hydrologic system of Yucca Mountain, an extensive surface-based testing program is planned to characterize the unsaturated zone. A series of infiltration tests has been designed to evaluate infiltration from simulated rainfall and ponding studies. Natural infiltration studies will use about one hundred shallow boreholes and artificial infiltration studies will collect data from over two hundred additional shallow boreholes. Unsaturated zone drilling and testing in approximately thirty deep boreholes are planned to characterize the spatial and temporal variability of hydrologic properties (approximately another forty boreholes will be used in the saturated zone hydrologic studies). Ten to fifteen boreholes are planned to provide data on the

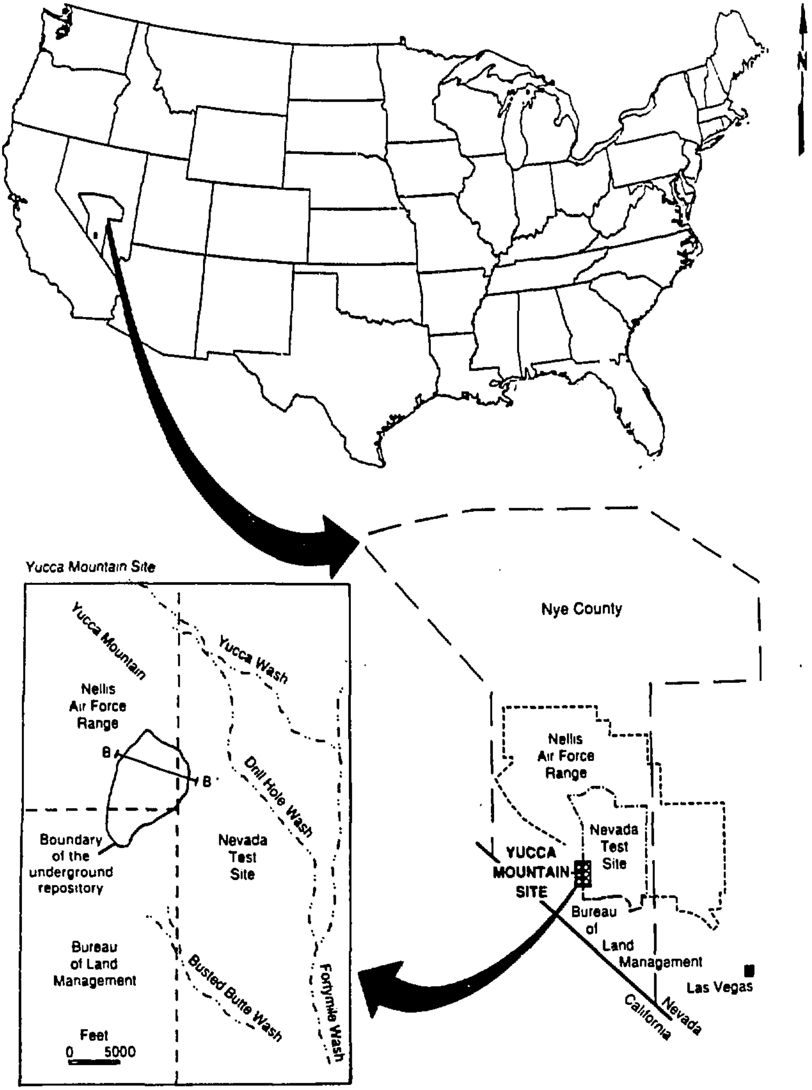

Figure 19.1. Location of the proposed Yucca Mountain site in southern Nevada. The line labeled B-B' marks the location of the cross section shown on Figure 19.2.

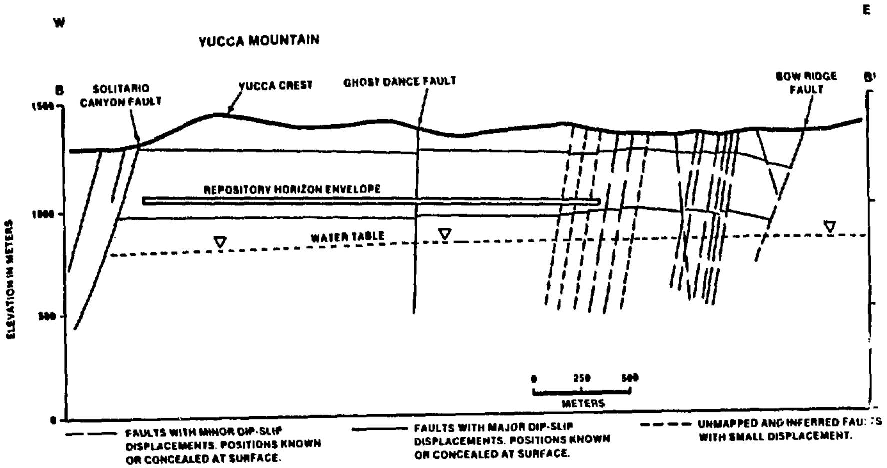

Figure 19.2. Schematic east-west cross-section through Yucca Mountain (labeled B-B' on Figure 19.1) illustrates the steeply dipping down-to-the west normal faults. Note the proposed location of the repository within the unsaturated zone.

regional hydrologic system, such as recharge at Fortymile Wash, the major wash along the eastern flank of Yucca Mountain. The number of planned boreholes is flexible since the drilling of some boreholes is dependent on the results of other scientific investigations.

Uncertainties associated with the site specific and regional tectonic settings must also be reduced in order to determine if the Yucca Mountain site is suitable as a high-level radioactive waste repository. Potential earthquake magnitudes and recurrence intervals associated with local Quaternary faults; vibratory ground motion parameters for the design of structures, systems and components important to safety; fault plane solutions derived from seismic monitoring records; and, the potential for surface faulting all need to be determined to help characterize the tectonic regime of the Yucca Mountain area. Other geologic uncertainties of the region include the degree of changes in ground-water conditions that may occur as a result of future tectonic events, the origins and ages of the calcite-silica deposits in faults and fracture zones, and the probability that the repository would be penetrated by an igneous intrusion. An integrated surface-based site characterization program has been designed to reduce these uncertainties and characterize the tectonic framework of the region. The Southern Great Basin seismic monitoring network consists of over 50 stations and is being upgraded with more stations, including more 3 component seismographs. The stations operate continuously and data are telemetered from the Yucca Mountain region to the USGS offices at the Colorado School of Mines (CSM) located near Denver, Colorado for processing and interpretation. Strong-motion recording instruments are also used to record seismic events. Thirty-two Quaternary faults have been recognized within a 1100 square kilometer area surrounding Yucca Mountain and 5 of these faults are within 15 kilometers of the proposed repository (Figure 19.3) (Swadley et. al., 1984). Geologic mapping and trenching will be conducted to detect and characterize possible Quaternary faults and to evaluate age and recurrence of movement. Evaluation of tectonic activity will directly influence the design of facilities important to safety such as the waste handling building and underground openings. Trenching of Midway Valley, which is located on the east side of Yucca Mountain, is planned to determine the nature of, and potential for, faulting at the candidate surface facility locations.

Future climatic conditions and their potential impact on the hydrologic system and erosion need to be addressed in order to evaluate the suit-

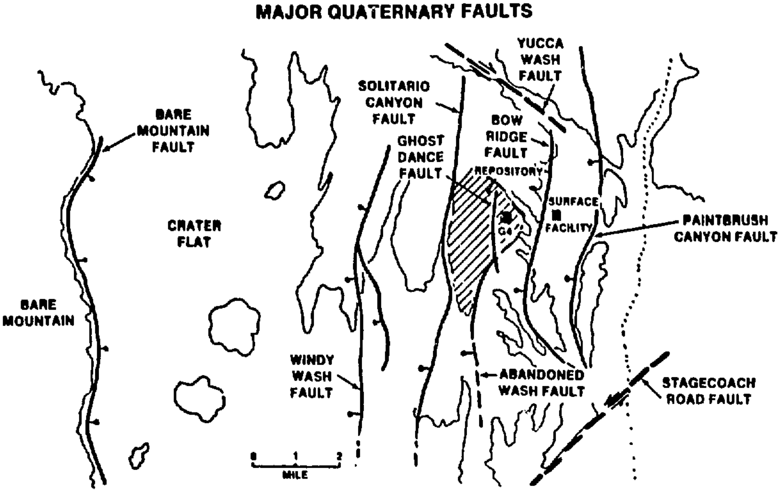

Figure 19.3. North-trending normal faults of Quaternary age (Ghost Dance fault is suspected to be Quaternary) within 15 kilometers of proposed repository. The repository's underground waste emplacement area is marked by the diagonal lines.

ability of Yucca Mountain as the site for the proposed repository. Presently southern Nevada has a very dry climate, but climatic conditions must be predicted 10,000 years into the future. Since climatic changes can affect the hydrologic system, the climatology investigations will have to be able to provide data on past climates and on conditions to be used to evaluate the impact of future climate changes on groundwater and surface-water hydrology, such as the effect of increased precipitation on flux through the unsaturated zone, changes in fracture/matrix flow, and the elevation of the water table.

Some of the surface-based activities to characterize and predict future climatic conditions include studies of the calcite and opaline silica deposits exposed in Trench-14 across the Bow Ridge fault located immediately east of Yucca Mountain. The origins of these deposits may indicate past geohydrologic conditions, including the possibility of saturated conditions. Hydrothermal processes, cool springs, pedogenic processes, and seismic pumping have been proposed as mechanisms for creating these deposits.

Lacustrine marsh deposits are located approximately 25 kilometers southwest of Yucca Mountain. Studies of these deposits and other surrounding lake, playa, and marsh deposits are planned. The results may indicate paleoclimate conditions that could be corroborated by analysis of terrestrial paleobotanic data. Climatological modeling will be used to study precipitation in the Southern Great Basin and predict future trends since changes in climate may also accelerate rates of erosion and infiltration. Precipitation and stream monitoring, regional paleoflood studies, unsaturated zone hydrochemical analyses, evaluation of past discharge areas, and studies of the incised drainages on and surrounding Yucca Mountain will be used to investigate the Quaternary regional hydrology. These activities will be integrated to characterize and predict future climatic conditions at Yucca Mountain and, if necessary, identify additional information needs. Historically, Nevada is a state which has experienced development of rich natural resource deposits, therefore, many questions need to be addressed to evaluate the uncertainties associated with the natural resource potential of the Yucca Mountain area. The uncertainty that will be evaluated is the possibility that future exploration for natural resources might lead to inadvertent human intrusion into the proposed repository. The potential for economic quantities of mineral and energy resources near the site, including groundwater, will have to be determined. The closest mining district lies approximately 15 kilometers west of Yucca

Mountain in the Bare Mountain mining district (Cornwall, 1972). Presently ground water is the only natural resource identified at the site, however, the future supply and demand for groundwater resources needs to be predicted (DOE, 1988).

A comprehensive surface-based testing program is planned to characterize the natural resource potential at the proposed site. Mineral and energy resource assessments will include evaluations of: geochemical analyses from surface samples, borehole cuttings and cores; geophysical/geologic data from tectonics and rock characteristics studies; heat flow and other geophysical data to assess the potential presence of geothermal energy resources; and data from stratigraphic and geochemical studies to assess the potential presence of mineral or hydrocarbon resources. The water resource assessment will include an evaluation of existing data on characteristics of groundwater supply at the site. The results and interpretation of these data will provide input to the analyses of the potential for inadvertent human intrusion into the proposed repository.

If Yucca Mountain is found to be suitable for the repository following site characterization, a license application to construct the repository will be submitted to the NRC. The current conceptual design of the proposed repository is based on acceptance of 70,000 metric tons of heavy-metal. Once filled, the repository will be decommissioned and the shafts, ramps, and all boreholes sealed, all surface facilities removed and the land reclaimed. Permanent markers will be installed around the site to identify the location of the repository, its contents, and associated dangers. The proposed repository has been designed to require no human maintenance following closure. Passive institutional records which include the layout and design of the repository will be maintained in a storage facility.

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40 CFR Part 191 (Code of Federal Regulations), (1985). Title 40, "Protection of Environment, Part 191, Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," Federal Register Vol. 50, No. 182, September 19, 1985, as amended.

Chapter 20

General Approach and Site Selection Criteria for Low- and Intermediate Level Radioactive Waste Repository in Yugoslavia

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20.1. Abstract

The necessity of radioactive waste repository construction in Yugoslavia has derived from the amounts of wastes generated at Nuclear Power Plant (NPP) Krško. The global concept of preliminary activities on the Radioactive Waste Repository Project includes four task groups: licencing activities, site selection, technology and design development activities, and safety assessment. Site selection is based on the evaluation of geotechnical, bioecological, social-geographic, regional planning and geostrategic criteria. In the geotechnical view, the criteria related to geomorphology, lithology, tectonics, seismicity, hydrogeology, meteorology, geochemistry, rock mechanics and pedology have been considered. All criteria have been evaluated in order to distinguish their exclusionary and weighted significance related to both planned repository design options: horizontal tunnel and tumulus/monolith. The site selection procedure includes six stages:

(1) Site screening of the total considered area (i.e. the areas of Yugoslav states of Croatia and Slovenia);

(2) Selection of possible macrolocations (each 200-400 km^2);

(3) Selection of closer macrolocation areas (each 40-50 km^2);

(4) Selection of microlocations (each 2-4 km^2);

(5) Choice of the most suitable microlocation; and

(6) Defining the site (i.e. position of facility: 15-20 hectares) within the best microlocation. In this way six possible microlocations have been chosen by considering, at the moment, only geotechnical criteria.

20.2. Introduction

Industrial low- and intermediate level radioactive wastes started to be generated in greater amounts in Yugoslavia after the start-up of the first (and only) nuclear power plant at Krško. This is the 632 MW(e) PWR Westinghouse plant that has been operational since 1982. However, radioactive wastes are generated in Yugoslavia not only in nuclear-energy facilities but also in other industries, medicine and nuclear institutes. This article will cover only the wastes rising from NPP Krško. In order to avoid difficulties with the normal operation of Krško in the future because of limited space for interim storage at the Krško site, the final radioactive waste repository has to be in operation in the shortest possible time.[2] Up to the end of 1986, there have been generated 6,112 drums of solidified and partially super-compacted low- and intermediate level radwaste drums. The details of low- and intermediate level wastes generation at the NPP Krško site are presented on Table 20.1.

The Radioactive Waste Repository Project in Yugoslavia was initiated in 1979. Since difficulties in the energy policy of the state have been increasing, the activities were delayed several times. Due to NPP Krško radwaste, interim storage is almost full, and the final repository has to be ready as soon as possible. Therefore, the electric energy boards of two Yugoslav republics (i.e. the separate states of Yugoslavia) - Croatia and Slovenia - as the owners of NPP Krško, established the Radioactive Waste Repository Department at the end of 1986. The essential aim of the Department is to organize and support four basic groups of project tasks: site selection, repository design development, safety analysis and licensing procedure. There are a few professional aspects included in the group of repository site selection activities: geotechnics

Table 20.1. Radioactive wastes generated at Krško nuclear power plant during the period 1982-1988

Waste type	Quantity (drums)	Activity		Volume (m^3)
		(Ci)	(Bq)	
S R	702	389.2	1.440 E 13	140
C W	45	1.8	6.740 E 10	9
E B	4634	136.5	5.051 E 12	927
F	65	24.9	9.225 E 11	13
S C	536	11.4	4.226 E 11	107
O	130	0.5	1.678 E 10	26
Total	6112	564.3	2.088 E 13	1222

Note: SR - spent resins, CW - compressible waste, EB - evaporator bottoms, F - filters, SC - supercompacted waste, O - others.

(geology and related aspects), bioecology, social-geography and regional planning. In the realization of the repository project, some of the most eminent Yugoslav companies have been engaged; consultation services were given to the experienced Bechtel company (USA), and all recommendations issued by the IAEA have been respected.

20.3. Repository Program for Low- and Intermediate Level Wastes

20.3.1. Regulatory Body

Since there has been no experience in radioactive waste isolation in Yugoslavia until now, some difficulties could be expected in the licencing procedure. The executive responsibility for the Radioactive Waste Repository Project has been given to electric energy boards of the republics of Croatia and Slovenia. Both, Croatian and Slovenian energy committees control the Project, being directly subordinate to the Governments of Croatia and Slovenia.

It must be stressed that this paper includes only data deriving from the activities performed on the Radwaste Repository Project controlled by the Radioactive Waste Repository Department at NPP Krško. Since the methods, criteria and results of investigations are not verified and validated by the authorities, they only have at this moment the standing of recommendations. Verification and validation of methods, criteria and available results by the authorities are under way.

20.3.2. Institutional Requirements for Repository Acceptance

Some of the basic institutional requirements, prescribed by a "Code of Practice on Conditions for Locating, Construction, Start-up and Operation of Nuclear Facilities" were issued in the Official Gazette of the Socialist Federal Republic of Yugoslavia, No. 52, in August 26, 1988. According to the Code, a radioactive waste repository is classified as a nuclear facility. The repository should be constructed in accordance with an approved design, quality assurance and safety assessment. The repository should be safe under: (a) all operational conditions (as defined by Yugoslav regulations for protection against ionizing radiation), and (b) in the event of an accident. Off-site radiation dose to an individual should be less than 10 microsievert per year if the event probability is less than 10^{-7} per year).

The repository site should be marked by: an impermeable host medium, an adequate distance from the repository bottom to the water-table, the absence of flooding at the site, and the absence of surface springs in the hydrogeologic area in the vicinity of the repository. Four time-stages of repository existence are foreseen as follows: an operational period (40 years), a closure period (10 years), a post-closure Period 1, i.e. an active institutional control (100 years), and a post-closure Period 2, i.e. an isolation period (150 years). In addition to Yugoslav legislation, some international recommendations (e.g. those issued by the International Atomic Energy Agency)[6,7] and U. S. regulations (10 CFR 61, 10 CFR 960, NUREG-0902)[8,10,11] have been considered.

20.3.3. Methods of Emplacement

There are two repository design options that are planned as alternatives in Yugoslavia: (1) horizontal tunnel, and (2) shallow ground burial - tumulus or monolith. The disposing unit in both cases is foreseen as a compact concrete block. In the horizontal tunnel option, the concrete block is cube-shaped, containing eight metal drums with immobilized radioactive wastes. In the other option (i.e. tumulus/monolith), the cubic concrete block contains eighteen radwaste drums. The multi-barrier protection system of radwaste units includes in both cases, except for a metal drum, a triple shielding system based on cement: (a) matrix and immobilization mixture inside the drums, (b) light concrete filling the inter-drum space within the disposing unit, and (c) heavy concrete outside the cover of the disposing unit.

Horizontal disposal in hard rock (i.e. "horizontal tunnel" option) will be performed as follows. The main tunnel with a series of lateral galleries will be assigned to concrete waste units disposal. By filling the space between disposal units and host rock, the homogeneity of the repository will be attained. Thus, another repository barrier can be established.[15] According to the amount of wastes to be disposed, the length of the main tunnel could be 300-500 meters (Figure 20.1).

For shallow ground burial, two methods of waste disposal are considered: "tumulus" and "monolith". Tumulus (i.e. an embankment-shaped structure) will be formed by concrete disposal units placed on a large concrete platform. The concrete blocks containing radwaste drums are to be covered by multi-stratified layers of gravel, sand, and clay with a PVC sheet on the top. All of the repository area is planned to be surrounded by a catchment system designed to collect run-off during the construction period, and to check the absence of water infiltrating into the structure after completion.

The monolith method of radwaste disposal is an engineered multi-barrier disposal system in which waste drums are placed in concrete canisters. Once stacked, they are bonded to one another by filling the space between the canisters with concrete. The bonded canisters are firmly held together to form a leak resistant concrete monolith.

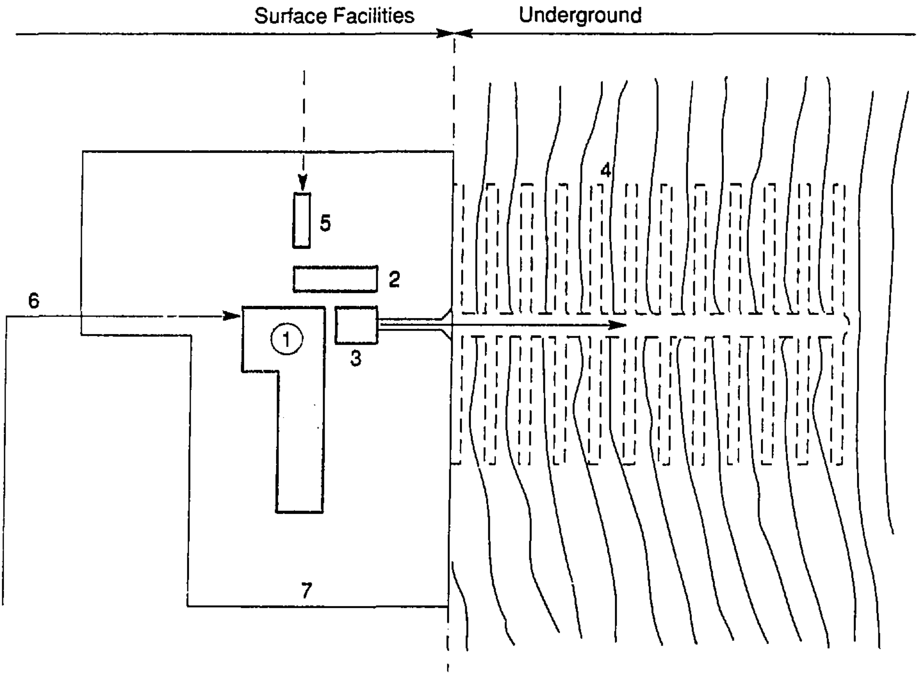
The design provides a rigid monolith that resists inadvertent intrusion.[18] The monoliths are planned to be lowered into the compartment having steel reinforcement on its bottom and sides to guarantee the strength of the structure. A catchment system is provided to collect any run-off or infiltrating water entering during the construction period and to check the absence of water infiltrating into the structure during the post-closure phase.[15] The depth of the repository based on shallow burial concepts will not exceed 5-10 meters (Figure 20.2).

20.3.4. Rock Types Considered

According to the geologic structure of the areas being considered (i.e. western regions of Yugoslavia) the following rocks were examined: granite, granodiorite, tuff, gneiss, schists (clayey, amphibolitic), and argillaceous rocks (clays, shales, siltstones, marls). It was established that argillaceous rocks are acceptable for the shallow-ground repository,[7] while the other lithologic types could be applied in the case of the tunnel repository option.[4] Due to the significance of geologic features in repository site characterization,[6,9] a brief description of the areas under consideration follows.

The territories of SR Croatia and SR Slovenia are, in the geologic and geomorphic sense, well-distinguished areas (Figure 20.3). There are three principal morpho-tectonic units in the area: Eastern Alps (northwest and northern Slovenia), Pannonian mass (northern Croatia) and Dinarides (southern Croatia and Slovenia).[1,3] While the Eastern Alps (mainly) and the Outer Dinarides are predominantly formed in carbonate (limestone, dolomite) rocks of the Jurasic and Cretaceous, and the Inner Dinarides includes a wide span of different rock types (sandstones, argillaceous, schists, conglomerates, limestones), the mountains of the Pannonian basin are composed mainly of igneous and metamorphic rocks of the Paleozoic. In the geomorphic sense, the Alps represent part of a high-mountain area with elevations higher than 2,000 meters (Triglav 2863 m, Skrlatica 2738 m, Mangart 2678 m, Grintavec 2558 m etc.). There are three Alpine morpho- tectonic groups in Yugoslavia: Julian, Karavanke and Savinja Alps. The geomorphic development of the Alpine region (as well as the Dinarides) started in the Paleogene, within the Alpine orogenetic stage.

East of the Alps, the Pannonian basin remained a lower area. In spite of its old lithology, the geomorphology of the Pannonian area is fairly young: in a genetic sense, the existing geomorphic forms are developed by subsidence of land masses covering the area limited by the Alps, Dinarides and Carpathians during the Alpine orogenetic stage in the lower Paleogene. Simultaneously, parts of the old Pannonian mass have been uplifted, existing today as one or more times remobilized and exhumed horst-mountains

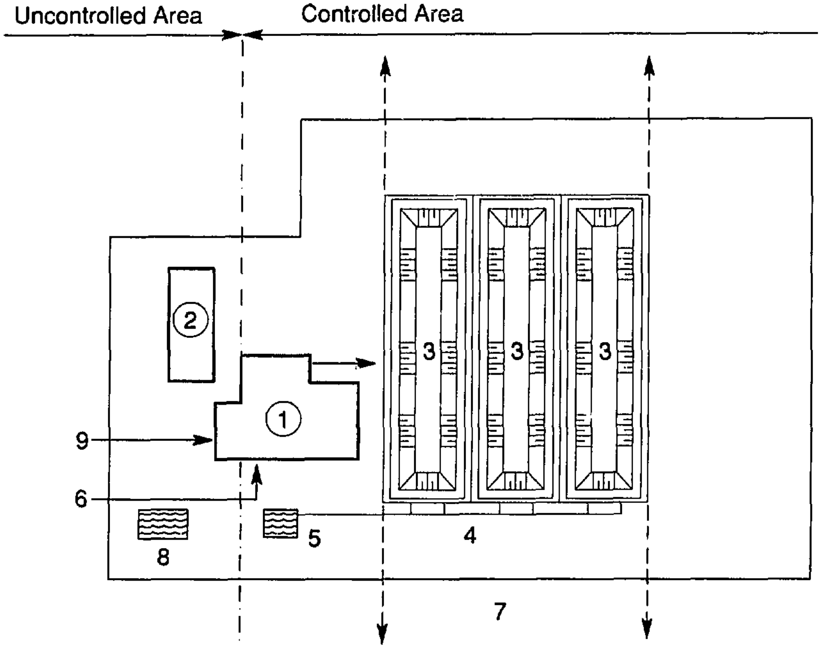


1. Main Building with Interim Storage
2. Manufacturing of Reinforced Concrete Containers
3. Final Treatment of Concrete Containers
4. Disposal Tunnels
5. Electricity
6. Waste Drums Access Route
7. Fence

Figure 20.1. Simplified layout of the planned radioactive waste repository Yugoslavia - Option 1: Horizontal Tunnel.

within an area of more than a thousand meter thick Tertiary deposits of the Pannonian basin. In the Croatian part of Pannonian basin the mountains of Psunj (984 m), Papuk (963 m) and Moslavačka (489 m) are the largest horst-massifs. Northward (Drava depression) and southward (Sava depression), they are limited by well-expressed depression zones. While the old Pannonian mass, represented by igneous (granites and related rocks) and metamorphic (gneiss, amphibolite, schists) rocks, is exhumed within areas of the above mentioned mountains, it is found even 3000-6500 meters deep under thick Tertiary deposits along depression zones. The Sava depression represents the morpho-tectonic border of the Pannonian mass with the Inner Dinarides to the south.

The structure of the Inner Dinarides is not simple. They are composed of all the main rock



1. Main Building with Interim Storage
2. Concrete Mixing Plant, Construction Material Storage and Workshop
3. Waste Repository Trenches
4. Repository Drainage Pipe-System
5. Precipitation-Pool with Pump-Station
6. Radwaste Acceptance, Categorization and Sorting Facility
7. Fence
8. Input Water
9. Electricity

Figure 20.2. Simplified layout of the planned radioactive waste repository in Yugoslavia - Option 2: Tumulus/Monolith.

types: igneous, metamorphic and sedimentary. Only the western part of this morpho-tectonic unit is found in the territories of Croatia and Slovenia. From the geomorphic standpoint, the region is characterize by hilly relief that surrounds the mountains of Zrinska (616 m) and Petrova (507 m). The southern parts of Croatia and Slovenia are included in the unit of Outer Dinarides, where carbonates (limestones, dolomite) with well-expressed karst relief prevail.

To the northeast, the perialpine/peripannonian parts of Slovenia (Zasavje hills, Haloze, Bizeljsko) and northwestern, peripannonian portions of Croatia (Macelj, Hrvatsko Zagorje, Vukomeričke) are hilly country interrupted by horst-type mountains like Bohor (1023 m), Ivanščica (1,061 m), Medvednica (1,033 m), Zumberačka (1,181 m), Kalnik (643 m) and some others.

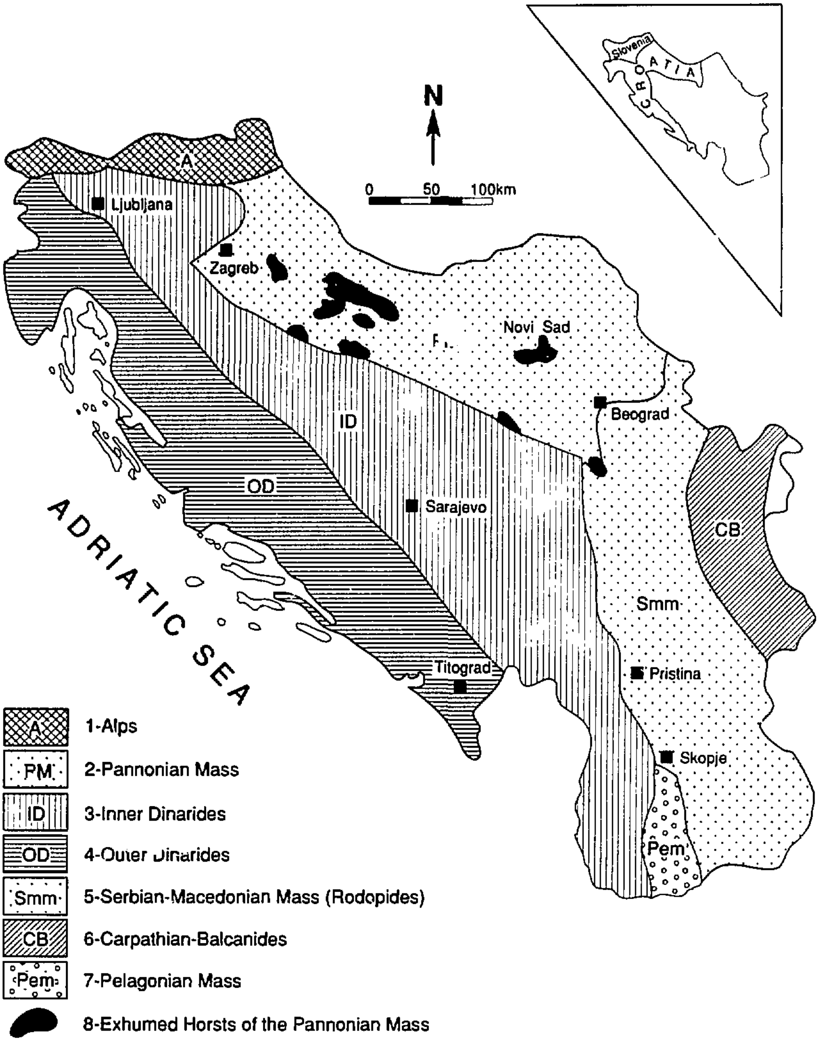


Figure 20.3. Map of geotectonic regions of Yugoslavia.

The areas of Croatia and Slovenia are characterized by intensive neotectonic movements. This was reflected by the intensive recent seismicity of the areas as well. Seismic zones of VII and VIII MCS prevail, but areas marked by IX or even X MCS are not rare. The main seismic zones are Zagreb, Ljubljana, Friuli (partially belongs to Italy), Carinthia (partially belongs to Austria) and the Adriatic coast (particularly at Rijeka, Makarska and Dubrovnik).

On the other hand, the southern parts of Croatia and Slovenia (about half of the area under consideration) are marked by a prevailing carbonate lithology (limestones, dolomites). Due to its irregular groundwater circulation, these areas are extremely unsuitable for siting a radioactive waste repository. Hence, the most convenient regions for a radwaste repository in Croatia and Slovenia are considered to be the remobilized and exhumed horst massifs of the Pannonian basin, the mountain areas of the Inner Dinarides, and parts of hilly areas with convenient lithology (clays, marls etc.) in the perialpine or peripannonian regions.

20.4. Geo-Criteria for Site Selection

There are two groups of geo-criteria under consideration: (1) criteria for site acceptability (i.e. exclusionary criteria), and (2) criteria for selection between possible sites (i.e. weighted criteria). Both groups are to be applied to each option for a repository site.

20.4.1. General Explanation of Geo-Criteria

The suitability of a repository site viewed from the geotechnical standpoint is estimated by means of an evaluation with respect to the following geoscientific fields: geomorphology, lithology, hydrogeology, seismology, tectonics, hydrology, geochemistry, rock mechanics and pedology. Besides geosciences, bioecology (identification of plant and animal species, determination of food chains, estimation of possible influence of repository to the biosphere), social-geography (settlement, population dynamics including birth and mortal rate, migrations, social and professional stratification etc.), regional planning (land use, areas of special natural and historic importance etc.) and national defense should be included in the global site characterization program.

20.4.2. Geo-Criteria for Site Acceptability

In the first stages of site selection, all exclusionary criteria have to be applied in order to reduce the areas according to their site acceptability. In the various stages of area-reduction, geo-criteria play the main role. The following is a listing of geotechnical exclusionary criteria as applied to each of the repository design options.[12]

Option 1: Horizontal Tunnel

Tectonics and Seismicity

(1) No site may be within an area of active faulting (active in the Quaternary). The repository should be situated more than 1 km from an active fault.

(2) The ground acceleration at the repository site may not exceed 0.3 g.

(3) No repository site may be within 3 km of an active geothermal area.

(4) No repository site may be within the area having a seismic magnitude of 6.5 or more (i.e. the intensity of IX MCS or more).

Hydrogeology

(1) No site may be within protected areas of major potable water resources (specified in Yugoslav Code of practice on zonation of potable water resources for sanitary protection). Consequently, no site may be within the areas of major aquifers.

Lithology and Geomorphology

(1) No site may be in areas with active or possible slope (rock falling, landsliding etc.) and proluvial (torrents) processes. All areas where lithology is not suitable (e.g. possibility of liquefaction caused by earthquake exists) should be excluded.

Hydrology

(1) The site should be safe from flooding, i.e. it should be beyond the limit of the 500-year flood.

Site Geometry

(1) The repository site must have a suitable host rock with minimal areal dimensions of 300 × 300 m.

Option 2: Tumulus/Monolith

Tectonics and Seismicity

(1) No site may be within an area of active faulting (active in the Quaternary). The repository should be situated more than 1 km from an active fault.

(2) The ground acceleration at the repository site may not exceed 0.3 g.

(3) No repository site may be within 3 km of an active geothermal area.

(4) No repository site may be within the area having a seismic magnitude of 6.5 or more (i.e. the intensity of IX MCS or more).

Hydrogeology

(1) No site may be within protected areas of major potable water resources (specified by Yugoslav Code of practice on zonation of potable water resources for sanitary protection). Consequently, no site may be within the areas of major aquifers.

(2) The depth to the water table must not be less than 5 m below the proposed bottom level of the repository.

Lithology and Geomorphology

(1) No site may be in the areas with active or possible slope (rock fall, landsliding etc.) and proluvial (torrents) processes, as well as in regions having high relief energy and/or inconvenient rock mechanic properties.

Hydrology

(1) The site should be safe from flooding, i.e. it should be beyond the limit of the 500-year flood and distant more than 500 m from any surface water.

Site Geometry

(1) The repository site must have a suitable host rock with minimal areal dimensions of 300 × 300 m.

Human Intrusion

(1) The site must avoid areas of oil and gas, ore/mineral and construction material exploitation.

20.4.3. Geo-Criteria for Selection between Sites

After the generally acceptable areas have been chosen, their correlative qualities will be estimated by applying the needed weighting criteria. Thus, all areas of interest will be ranked according to their suitability. A list of weighting criteria for both of the possible repository design options is given below.

Option 1: Horizontal Tunnel

Hydrogeology

(1) The groundwater at the site should have as long a flow path to the biosphere as possible.

(2) The water-table should have as small fluctuations over time as possible.

Tectonics and Seismicity

(1) The repository site should be as far from an active fault as possible.

(2) The repository site should have as favorable seismic properties (ground acceleration, low earthquake frequency etc.) as possible.

Lithology

(1) The repository site should have as acceptable a petrology as possible.

(2) The host rock should have minimal fractures, joints or any other discontinuities.

(3) The host rock should be as fresh and unweathered as possible.

(4) The host rock should possess favorable mechanical and geochemical properties.

Geomorphology

(1) The site should have as low a probability of active or potentially active slope processes that would impact the access tunnel portal or surface facilities as possible.

Site Geometry

(1) The host rock should have at least 30 m of unweathered, stable rock above the repository level and at least 30 m of rock below.

Human Intrusion

(1) The repository should avoid areas of oil, gas and ore/mineral exploitation.

Option 2: Tumulus/Monolith

Hydrogeology

(1) The water-table should have as small fluctuations over time as possible.

Geomorphology

(1) The site should have as low a probability of active or potentially active slope processes as possible, low erosion rate and the lowest

possible surface subsidence and potential for soil collapse.

(2) The site should have as low relief energy as possible.

Tectonics and Seismicity

(1) The repository site should be as far from an active fault as possible.

(2) The repository site should have as suitable seismic properties (ground acceleration, low earthquake frequency etc.) as possible.

Site Geometry

(1) The site should have as thick a suitable host medium (layer) as possible, but not less than 20 m.

(2) The bedrock at the repository site should be as deep from the facility bottom as possible, but not less than 50 m.

Hydrology

(1) The repository site should be located in the area where the ratio of the evaporation to precipitation is as high as possible.

Human Intrusion

(1) The site should avoid areas of excessive ground water withdrawal (irrigation).

20.5. The Procedure of Site Selection

The global concept for repository site selection consists of four task groups:[5] licensing activities, site selection, technology and design development activities, and safety assessment (Table 20.2). The final repository site - as the aim of site selection activities - will be derived considering the following criteria: geotechnics, bioecology, social-geography, regional planning and national defense. All these groups should be evaluated and referred to the accepted repository design option, and this will form input data for safety assessment (Table 20.3). The accepted site selection concept in Yugoslavia (Table 20.2) consists of twelve tasks, grouped into three stages.

Stage One

(1) Collection of basic geotechnical and non-geologic data in the territories of Croatia and Slovenia;

(2) Definition, verification and validation of basic geotechnical, bioecological, social-geographic and urban-planning criteria;

(3) site-screening of Croatia and Slovenia in order to select macrolocations (≈ 200-400 km^2) and "smaller" macrolocation areas (≈ 40-50 km^2);

(4) Definition, verification and validation of additional geotechnical and bioecological exclusionary criteria;

(5) Geo-investigations and bioecological surveying on the "smaller" macrolocation areas;

(6) Selection of suitable microlocations (≈ 2-4 km^2).

Stage Two

(1) Definition, verification and validation of weighted geo- and bioecological criteria;

(2) Ranking of the microlocations after their geo- and bioecological acceptability;

(3) Definition, verification and validation of exclusionary and weighted non-geotechnical criteria;

(4) Final ranking of proposed microlocations.

Stage Three

(1) Final site characterization program and detailed geo-investigations on the microlocation;

(2) Final site selection.

In order to find the most suitable radwaste repository site, the characterization of the territories of Croatia (56,538 km^2) and Slovenia (20,251 km^2) is being performed in several stages.[13,15,16] After applying the requisite exclusionary and weighting criteria, the areas under consideration will be reduced to suitable microlocations from which the final repository site will be chosen (Table 20.4).

All geologic investigations resulting in the selection and ranking of possible repository microlocations[12,13] have been performed by Yugoslav companies INA-PROJEKT in Zagreb and GEOLOKI ZAVOD in Ljubljana. We have also had the benefit of consulting services from the U. S. Bechtel National company in San Francisco.

The aim of the site selection activities was to find those areas that meet the basic site requirements as follows:

(1) the site characteristics should be in keeping with the proposed repository design;

Table 20.2. Global concept of preliminary activities for the Radioactive Waste Repository Project.

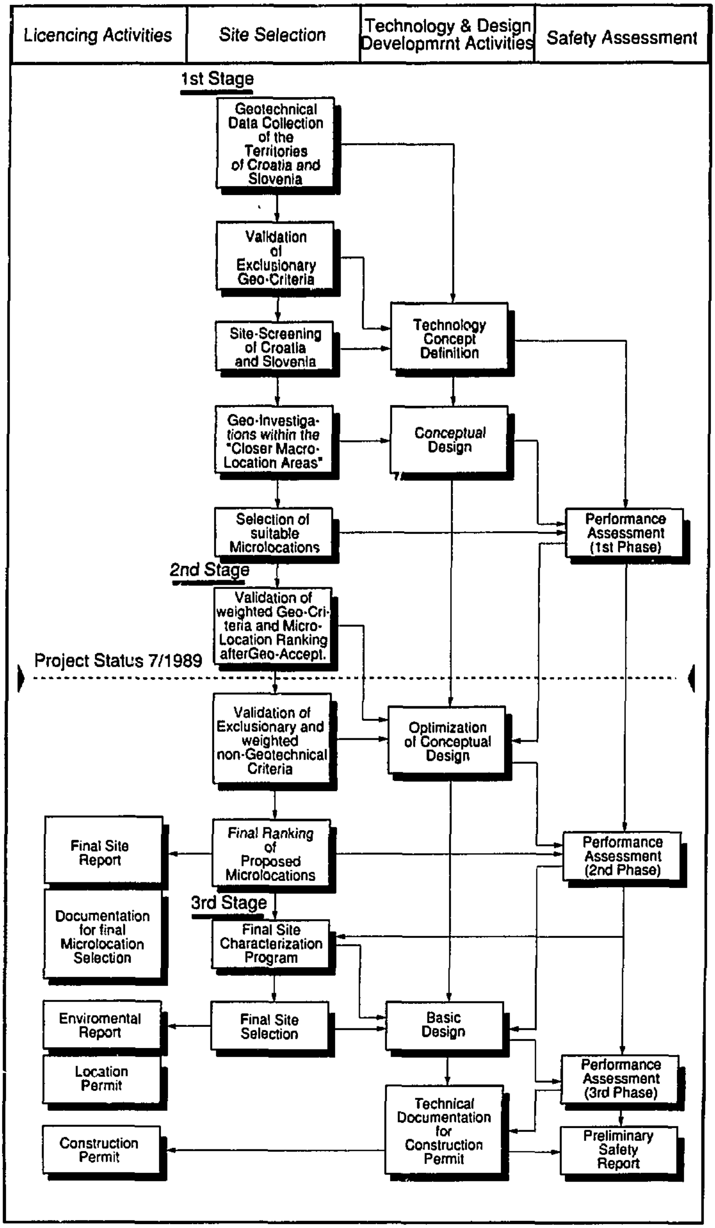


Table 20.3. The criteria evaluation for radwastse repository site selection.

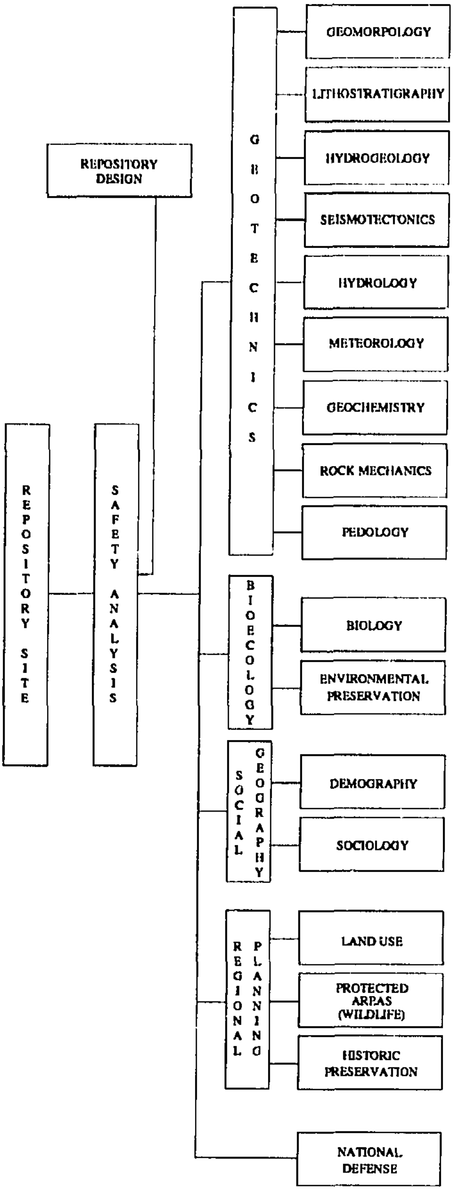
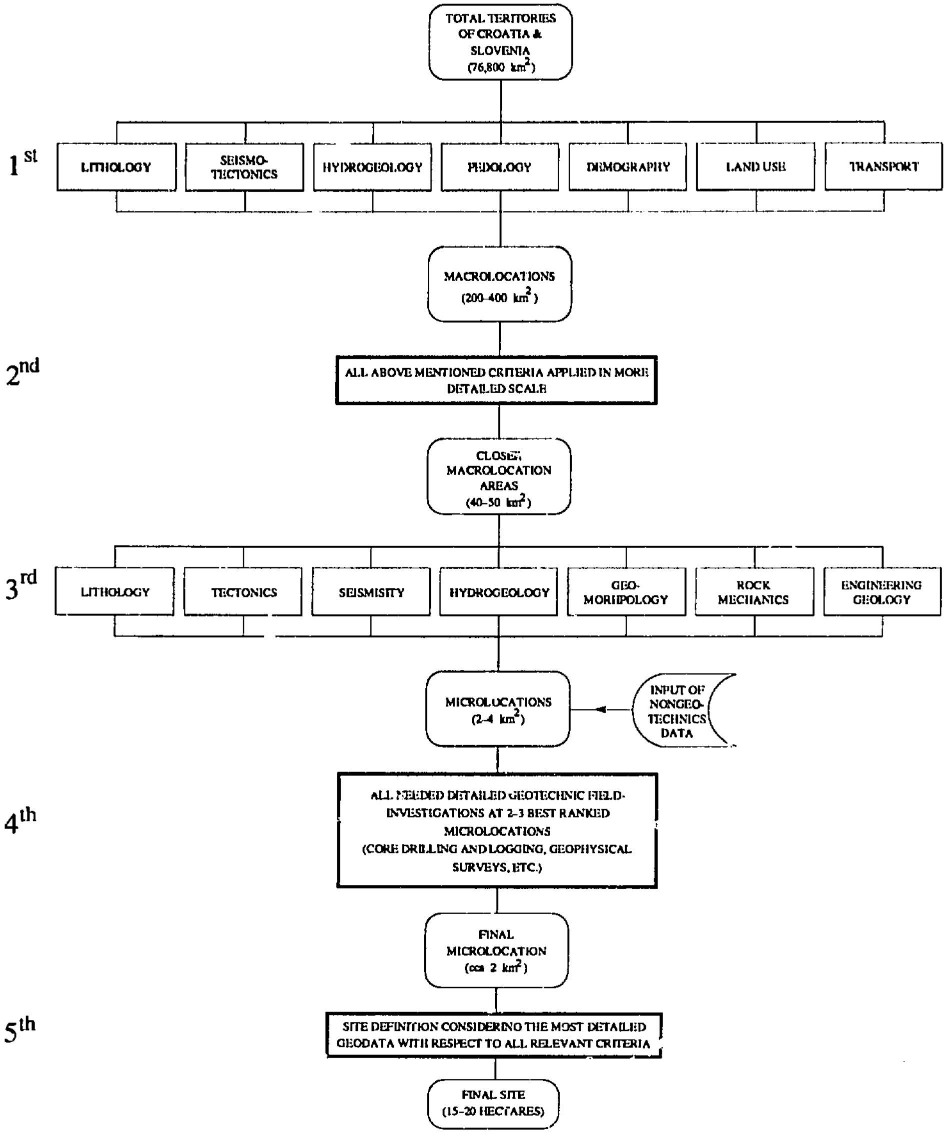


Table 20.4. Global concept of geotechnically related site selection activities.



(2) the site should be suitable for the performance of safety assessment and corresponding environmental protection requirements;

(3) the land use options at the proposed areas should not be in conflict with repository operation;

(4) the site should have a positive cost-benefit requirement related to the repository operation. An examination of the complementary role of host rock and designed safety barriers should be performed.

The ranking of proposed microlocations (i.e. those resulting from the originally applied exclusionary criteria) is to be carried out by means of a weighting criteria. The following method of ranking has been adopted. Each criterion in the ranking process, including the sub-criteria, is assigned a weighting factor. The value of each factor is set according to its significance with respect to all other factors involved in the radioactive waste repository site. The sum of these factors should be 100.

The distribution of weighting factors that was adopted is as follows, where the first number refers to the Tunnel option and the second to the Tumulus/Monolith option: hydrogeology 30/25, tectonics and seismicity 25/25, lithology 15/15, geomorphology 10/15, site geometry 10/10, hydrology 5/10, and human intrusion 5/5 points. Each criterion includes one or more sub-criteria, and these have been ranked by a quality factor ranging from 1, for the worst, to 5, for the best property according to the acceptability of features at each location. The sum of the products of all considered criteria defines a suitability rank for a location (Table 20.5).

20.6. Present Status of Site Reconnaissance Program

As of now, the following site characterization and site selection tasks have been performed by the Radioactive Waste Repository Department:

(1) definition and internal verification of the necessary exclusionary and weighted geotechnical criteria for both repository options;

(2) site-screening of both Croatia and Slovenia and the selection of possible macrolocations and smaller macrolocation areas;

(3) performance of basic geotechnical field-investigations at the smaller macrolocation areas and selection of possible microlocations;

(4) ranking of the possible microlocations as to their geotechnical suitability;

(5) site characterization program for detailed geotechnical investigations;

(6) bioecological investigations at all possible macrolocations.

In order to distinguish the most suitable locations, the following geotechnically related tasks have been performed:

(1) Interpretation of small scale (1:1,000,000, 1:500,000) and medium scale (1:200,000, 1:100,000) maps in terms of the selection criteria.

(2) Interpretation of remote sensing data (Landsat 5, Thematic Mapper).

The results on the scales of: 1:500,000, 1:200,000 and 1:100,000 have been presented using the following techniques; Colour Additive Composite, Colour Principal Component Composite, Colour Ratio Composite, and Principal Component imagery with filtering and single band images.

The purpose of this interpretation was: (a) to detect the preliminary status (i.e. on-site status before repository build-up) of the considered area; and (b) to determine the principal geomorphic, lithologic, hydrogeologic, tectonic, hydrologic, pedologic and floristic features of the areas under investigation.

(3) Geologic mapping of possible locations.

As a result of above-mentioned tasks combined with field-work, several geologic (lithologic, tectonic, hydrogeologic), geomorphic (relief energy, slope inclinations, morphodynamics) and hydrologic maps of possible locations on a scale of 1:50,000, 1:25,000 and 1:10,000 have been prepared.

(4) Inventory of springs and wells.

All springs and wells and their locations were presented on the large-scale maps. Their capacity, water temperature, depths (for wells) and regime, as well as their relation to corresponding aquifers were considered.

(5) Surface sampling.

The necessary quantity of surface samples has been collected at all possible locations. Mineralogic, petrographic, sedimentary, micropaleontologic, rock-mechanic, and geo-hydrochemical (groundwater chemistry related to composition, radioactivity,

Table 20.5. Ranking of proposed sites by means of the weighting criteria

Criteria	Weighting Factor	Location 1		Location 2		Location 3		Location 4		Location 5		Location 6	
		Quality Factor	Criterium Accept-ability	Quality Factor	Criterium Accept-ability	Quality Factor	Criterium Accept-ability	Quality Factor	Criterium Accept-ability	Quality Factor	Criterium Accept-ability	Quality Factor	Criterium Accept-ability
1. Hydrogeology (30)													
Groundwater flow path	20	5	100	5	100	5	100	5	100	5	100	5	100
Water-table oscillations	10	5	50	5	50	5	50	5	50	5	50	5	50
2. Tectonics & seismicity (25)													
Distance to an active fault	10	4	40	4	40	2	20	2	20	1	10	1	10
Seismic properties	15	4	60	4	75	3	45	3	45	2	30	3	45
3. Lithology (15)													
Acceptable petrology	6	5	30	5	30	4	24	3	18	3	18	3	15
Minimal fracturing	4	1	4	1	4	1	4	4	16	4	16	4	16
Weathering rate	3	3	9	3	9	3	9	3	9	3	9	3	9
Geomechanics & Geochemistry	2	5	10	5	10	4	8	3	6	3	6	3	6
4. Geomorphology (10)													
Slope stability	10	4	40	4	40	3	30	1	10	1	10	1	10
5. Site geometry (10)													
Host rock integrity	10	2	20	2	20	1	10	3	30	3	30	3	30
6. Hydrology (5)													
No stream destruction	5	5	25	5	25	5	25	5	25	5	25	5	25
7. Human intrusion (5)													
No natural resources	5	3	15	3	15	1	5	1	5	1	5	1	5
Total	100		403		418		330		334		309		324
Acceptability (Rank)		2		1		4		3		6		5	

age of groundwater etc.) analyses have been carried out.

(6) Surface mapping for lithologic profiles.

Surface mapping to obtain lithologic profiles (eg. at quarries, excavations, sheer rocks etc.) at possible locations have been analyzed in order to examine the surface lithology. The profiles provide information on profile direction, inclination of the mapped layers and faults/joints, lithology of the layers, and dimensions of areas mapped.

(7) Basic meteorologic data.

Air temperatures and precipitation have been measured over a 10-30 year period and have been compiled for all possible locations. Additionally, water-balances (recharge, discharge, evapotranspiration- and infiltration rate) have been calculated for each location.

(8) Numerical modeling.

Site numerical modeling is part of performance assessment but at the moment, only the first stage has been performed. This task is accomplished according to the requirements of computer codes IMPACTS (for the tumulus/monolith option) and SUTRA (for the horizontal tunnel option). The real (i.e. measured) or, at least, generic input data on geology (especially, hydrogeology), meteorology and demography have been used. A sensitivity analysis has been performed at the same time. As a result, both of the design options (i.e. tumulus/monolith and horizontal tunnel) have been assessed as safe, according to the requirements given in 10 CFR Part 61, and ICRP recommendations[5,16,17]. Numerical analysis of seismic risks in all regions of interest for a 300-year period has already been performed, as well.

Based on the results of these investigations, six microlocations (L1-L6) are estimated as suitable. All of them were subsequently weighted in accordance with the above described procedure (Table 20.5). Some of their basic geologic properties are presented in Table 20.6.

20.7. Remaining Activities on Site Reconnaissance

The aim of the activities that follow, as part of the site Characterization Plan, is to perform detailed field-investigations that include sampling and large-scale mapping at two or three of the best ranked microlocations. In this way precise information on each microlocation will be provided. Hence, a definite repository site of about 15 hectares will be selected within the 2-3 km^2 area of the most favorable microlocation.

To define the final microlocation and select the repository site, the following tasks[14] are to be carried out:

Table 20.6. Some of the basic geologic properties at proposed sites

	Host Rock				Groundwater				Seismicity nearest active fault (MCS/km)
	Type	Permeability (m/s)	Porosity (%)	Coef. of Thermal Conduct.	Type	Mineralization (mg/l)	Radioactivity (Bg/kg)	Age Dating (years)	
L-1	Gneiss	10E-11 - 10E-13	0.74-6.50	0.004	Calcium-Hydrocarbonate	91.7	135.7	5	VIII* 1
L-2	Granite	10E-11 - 10E-13	0.74-6.50	8E-3 - 1E-2	Calcium-Hydrocarbonate	312.0	228.9	6-7	VI* 5
L-3	Amphibolite Schist	3E-17 (horizontal)	1.94-2.66	-	Calcium-Hydrocarbonate	156.1	70.7	2	VII* 12
L-4	Argillaceous Schist	7.8E-21 - 6E-19	2.9-10.2	-	Calcium-Hydrocarbonate	159.7	113.3	6	VIII* 2
L-5	Argillaceous Schist	7.8E-21 - 6E-19	2.9-10.2	-	Calcium-Hydrocarbonate	145.8	105.6	5-6	VIII* 1
L-6	Argillaceous Schist	7.8E-21 - 6E-19	2.9-10.2	-	Calcium-Hydrocarbonate	157.1	106.3	5-6	VIII* 1

(1) Project schedule (list of planned tasks, coordination and supervision),

(2) Research and review,

(3) Quality assurance and quality control plan,

(4) Microlocation and site-specific field surveys, including:

    General field reconnaissance and land surveying,

    Detailed site topographic map preparation (scales of 1:10,000, 1:5,000, 1:1,000),

    Geologic mapping,

    Surface hydrology mapping,

    Paleontological surveying,

    Surface geophysical investigation,

    Ore/mineral deposits land assessment,

    Soil surveys,

    Meteorological/air quality station installation,

    Seismologic station siting,

    Well inventory,

    Monitoring well installation,

    Deep exploratory boreholes,

    Aquifer testing,

    Geotechnical boreholes,

    Soil monitoring probes and field infiltration tests.

(5) Monitoring and sampling program, including:

    Ground-water monitoring and sampling,

    Soil/rock probe monitoring,

    Water age dating,

    Soil/rock age dating,

    Atmospheric radiological monitoring and sampling.

(6) Laboratory testing program, including:

    Soil/rock analysis,

    Ore/mineral potential validity analysis,

    Ground-water analysis.

During the characterization work, maps, graphs and data tables should be generated: (a) geologic maps, cross sections and stratigraphic columns; (b) geomorphic (morphographic, morphodynamic) maps; (c) geophysical data plots and cross-sections; (d) boring and well logs; (e) maps of historic earthquake epicenters (and modified Mercalli intensity maps); (f) tabulation of earthquake epicentre data; (g) well hydrographs; (h) water quality data tabulation; (i) records and maps from the well inventory and data search; (j) meteorological site- and historical records; (k) watershed and flood hazard maps; (l) ground-water contour maps; (m) meteorologic data tabulation, graphs and charts; (n) laboratory test results (chemical, radiological and physical testing); and (o) boring logs and maps.

20.8. Conclusions

The Radioactive Waste Repository Project in Yugoslavia is faced with several obstacles deriving from uncertainties in the nuclear-energy program of the country. The most urgent problems that must be solved are: (a) completion of licencing procedure, (b) reevaluation and validation of geotechnic and non-geologic criteria, (c) development of a well-balanced method of site-selection and (d) definite selection of repository design. This paper presents the status of the Radioactive Waste Repository Project managed by the Radioactive Waste Repository Department at Nuclear Power Plant Krško. The results of the investigations described here are all considered important, but they will necessarily be subject to approval by the federal authorities.

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Chapter 21

U. S. Nuclear Regulatory Commission's Strategy for Identifying and Reducing Uncertainties Important to Licensing a High-Level Radioactive Waste Repository: Geological Examples Applicable to the Yucca Mountain Site, Nevada

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21.1. Abstract

The U. S. Nuclear Regulatory Commission has developed a regulatory strategy to help ensure that the U. S. Department of Energy submits a complete and high-quality license application to construct a high-level radioactive waste repository and that NRC makes a decision on the application within three years of its receipt. NRC has an on-going program to identify and reduce regulatory, technical and institutional uncertainties. NRC is responsible for reducing regulatory uncertainties and is doing so by refining the existing regulations (i.e., rulemaking) and by writing guides and technical positions to specify and clarify acceptable methods of compliance. Examples of NRC documents regarding geoscience areas are: site characterization analysis of DOE's plan to characterize Yucca Mountain, Nevada; technical position on use of tectonic models in the assessment of performance of a geologic repository; and draft rulemaking-clarification of what is meant by anticipated and unanticipated processes and events.

21.2. Purpose of Strategy to Reduce Uncertainties

The U. S. Nuclear Regulatory Commission (NRC) staff has prepared a regulatory strategy to guide its High-Level Waste Repository Licensing Program.[1] This strategy consists of approaches for identifying uncertainties in the existing regulatory framework, approaches for further refining the regulatory framework and to reduce uncertainties, using a mix of rulemaking, Technical Positions, and a Regulatory Guide. The resulting refined regulatory framework will help ensure that the U. S. Department of Energy (DOE) submits a complete and high quality License Application and that NRC makes a construction authorization decision within the three-year time period, mandated by the Nuclear Waste Policy.Act[2]

21.3. Identification of Uncertainties

The staff's identification of regulatory, technical and institutional uncertainties within the existing regulatory framework has been and will be a continuous process. The approaches the NRC staff uses to identify uncertainties include: (1) results of prelicensing technical reviews of DOE's program; (2) results of NRC contractor research; (3) suggestions by DOE, State of Nevada, and other parties; (4) a systematic analysis of the existing regulatory framework; and (5) iterative performance assessments (i.e., modeling of repository system performance at the Yucca Mountain site related to compliance with the performance objectives of 10 CFR Part 60).[3]

21.4. Reduction of Uncertainties

The staff currently plans to use a variety of approaches to reduce uncertainties.[1] Rulemakings will be the primary mechanism to resolve regulatory uncertainties where the meaning of a requirement or definition in 10 CFR Part 60 is subject to different interpretations or where what is needed to demonstrate compliance with a requirement is not clearly stated in the requirement itself. Rulemakings will be used where authoritative and binding resolution is considered to be needed. Technical positions may be used where binding resolution is not needed. A Regulatory Guide will be prepared to give guidance on the format and organizational structure for the information to be included in the License Application. Technical positions will focus primarily on technical uncertainties related to acceptable methods for how compliance should be demonstrated for selected areas that are both controversial and significant to repository performance. These technical positions will consist of the criteria that will be guidance to DOE and that the staff will use to review the methods DOE develops to resolve the technical uncertainties. Both the Technical Position mechanism and the use of criteria (rather than prescribing specific methods) will continue to allow DOE flexibility in its application of state-of-the-art technology to demonstrate compliance. The staff will also use prelicense review and consultation to give guidance to DOE for reducing technical uncertainties.

To the extent practicable, the staff will reduce significant regulatory uncertainties with final rulemakings and technical positions by 1992 which is generally when DOE will begin preparing its license application. Draft technical positions and proposed rulemakings, however, will give DOE and other parties an early opportunity to understand and comment on the staff's evolving position. Finally, the process of developing the above-mentioned rulemakings and guidance documents will involve all interested parties, including targeted technical groups, so that their questions and concerns can be addressed in an open and documented manner before licensing.

21.5. Scope of Geological Sciences Programs

The geological sciences programs and activities of NRC's High-Level Waste Repository Licensing Program are based in the Office of Nuclear Material Safety and Safeguards and the Office of Research.[4] The approximately 20 geoscientists are a portion of the agency's approximately 60 full-time technical staff resources devoted to the High-Level Waste Repository Licensing Program. The geoscientists identify and manage the resolution of regulatory, institutional and technical uncertainties in geology, seismology, geophysics, mineral and water resources, surface water, groundwater, climatology, meteorology, geochemistry and radionuclide transport. Contractor resources are available to support its needs to perform technical analyses and to conduct research that will facilitate uncertainty reduction. Most of those resources are based at the Center for Nuclear Waste Regulatory Analyses.[5]

21.6. Status of Geoscience Rulemakings, Technical Positions, Regulatory Guides and Document Reviews

The NRC staff anticipates resolving the following geoscience regulatory uncertainties by rulemakings: anticipated processes and events, and unanticipated processes and events,[6] definitions of "geologic setting,"[6] groundwater travel time, and disturbed zone.

The following Technical Positions have been published to assist DOE in addressing various geoscience technical uncertainties: Issue-Oriented Site Technical Position for Nevada Nuclear Waste Storage, Investigation[7] determination of radionuclide solubility in groundwater for assessment of high-level radionuclide waste isolation[8] and determination of radionuclide sorption for high-level waste repositories.[9]

Technical Positions are under development to guide DOE's resolution of the following technical uncertainties: radionuclide transport, chemical interactions in fractured unsaturated rock, use of tectonic models,[10] earthquake hazard evaluation, probabilistic seismic hazard analysis, volcanic hazard analysis, natural resources assessment, geomorphic analysis, and scenario identification and screening. Geoscience portions of a Regulatory Guide on the Format and Content of Site Characterization Plans (SCPs) have been published,[11] and geoscience portions of a Regulatory Guide for the Format and Content of the License Application are under development.

NRC has commented upon DOE's Consultation Draft Site Characterization Plan for Yucca Mountain.[12] DOE has issued the statutory Site Characterization Plan,[13] NRC issued a report of its analysis of the SCP; the report is the Site Characterization Analysis (SCA).[14] The concerns and related recommendations that the NRC presents in the SCA will be entered in an open item tracking system such that progress toward closure of those items with DOE can be followed by any interested party. Technical meeting with DOE and State of Nevada will focus on DOE's resolution of these open items.

21.7. Selected Geological Examples of Regulatory and Technical Uncertainties

The following geological examples of uncertainties important to licensing were selected to illustrate NRC's strategy for identifying and reducing such uncertainties. Examples from other areas, such as hydrology and geoengineering, could be similarly illustrative of the strategy. No inferences should be drawn about the significance of one of these examples relative to licensing priorities or to another uncertainty.

21.7.1. Example of Technical Uncertainties Reduction by Document Review Guidance: Characterization of Faulting at Yucca Mountain

NRC regulations require that DOE's license application contain analyses to determine the degree to which each of the favorable and 24 specified potentially adverse conditions, if present, has been characterized, and the extent to which it contributes to or detracts from isolation.

One potentially adverse condition at the Yucca Mountain site that DOE is investigating is "structural deformation such as uplift, subsidence, folding and faulting during the Quaternary Period" (60.122 (c)(11)). DOE's Site Characterization Plan[13] describes a variety of investigations of faulting. Reviews of the SCP have led the NRC staff to raise concerns that some of the investigations of faulting, as planned, would not provide results sufficient to meet the following requirements: that faulting be investigated to the extent that Quaternary faulting may be present, but still be undetected; analyses and assumptions used might not underestimate effect of faulting on waste isolation; and faulting be shown either not to significantly affect the ability of the repository to meet the performance objectives, or is compensated by favorable characteristics or can be remedied.

The NRC considers that the following approaches to investigating faulting, if characterized as planned, would appear likely to significantly underestimate the effects of faulting:[14]

(1) use of fault slip rates which tend to obscure episodicity of faulting,

(2) consideration of faults as single strands of narrow width rather than as parts of broad fault zones which could have a significant impact on repository performance, and

(3) assumption that future faulting will follow old fault patterns.

In addition to identifying the above concerns in the SCA, technical meetings are planned for NRC, DOE and the State of Nevada to discuss resolution of these concerns.

Thus, NRC uses prelicensing review of documents to provide guidance to DOE for reducing technical uncertainties that help to ensure the submittal of a complete and high-quality License Application. The reviews result in documented concerns and recommendations that become the topics of technical meetings geared toward effecting resolution of the concerns.

21.7.2. Example of Technical Uncertainty Reduction by Use of Technical Position: Uses of Tectonic Models

In the Consultation Draft Site Characterization Plan (CDSCP) and the Site Characterization (SCP), DOE has indicated that it intends to use models in the performance assessment process. As a result, DOE is required, under 10 CFR Part 60 (Section 60.21 and 60.101)[3] to provide thorough support of those models. The NRC staff has noted that the programs as described in the CDSCP may favor collecting data to support the preferred model, rather than collecting data necessary to establish the range of geologic conditions at the site or to determine what the preferred model should be.

NRC decided to address this concern by providing guidance to DOE in the form of a technical position.[10] The objectives of the Tectonic Models technical position are to outline the regulatory requirements for support of tectonic models, to discuss the implementation of the requirements, and to suggest a process for integrating tectonic models into data collection activities of the Site Characterization program.

The technical position consists of the following criteria related to the support and implementation of tectonic model(s) in performance allocation and performance assessment, as follows:

(1) Tectonic models should form the basis for preliminary performance allocation, with respect to tectonic factors, and for prioritizing those investigations that have the greatest potential for resolving issues associated with tectonic features, events, or processes that could lead to major licensing concerns or to substantial change in the site characterization program.

(2) The iterative process of model creation, modification, abandonment, and model confirmation should begin during site characterization and continue until permanent closure (10 CFR 60, Section 140 and 141). This process will permit field conditions encountered during various phases of the program to be taken into consideration.

(3) A full range of tectonic models supported by existing data should form one of the principal bases for planning tectonic investigations carried out during site characteri-

zation and for assessing the ability of the site to meet the performance objectives identified in 10 CFR Part 60. Such alternative tectonic models should:

  (a) form one of the principal bases for input related to tectonics in the development of a comprehensive list of scenarios needed to show compliance with 10 CFR Part 60, Section 112; and
  (b) form one of the principal bases for input into the identification of anticipated processes and events and, therefore, in the design of the engineered barrier system needed to show compliance with 10 CFR Part 60, Section 113.

(4) The iterative process of model creation, modification, abandonment, and confirmation and the identification of processes and events that will be considered to be anticipated processes and events should be based on deterministic considerations, not probabilities.[15] For example, the identification of volcanism as an anticipated process in the geologic setting should not be based on an assessment of the likelihood of occurrence, but on a deterministic assessment of whether volcanism has occurred in the geologic setting during the Quaternary.

(5) DOE should demonstrate that the program of site characterization, designed to provide support for, and differentiate between alternative tectonic model(s), will provide data that are sufficiently representative of the events and processes in the geologic setting that the full range of conditions at the site can be identified and their effects on waste isolation can be assessed.

The technical position discusses the need for DOE to favor deterministic over probabilistic methods and the relationship between tectonic models and identification of anticipated processes and events and unanticipated processes and events. Probabilistic hazard analysis is considered to be a valuable supportive tool in the consideration of credible processes and events included in tectonic models. However, the Commission has recognized (Federal Register, Vol. 48, No. 120, June 21, 1983) and the staff has reiterated[15] that the "Identification of anticipated and unanticipated processes and events for a particular site will require considerable judgment and will not be amenable to accurate quantification, by statistical analysis, of their probability of occurrence." In an assessment of tectonics using a probabilistic approach for determining the likelihood of events and processes that might effect the performance of a repository, Calendar (Sandia 86-0196) said that: "At present, no tectonic or seismologic method is completely adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity at a repository site."

Thus, the proposed technical position is intended to reduce technical uncertainty by establishing criteria for an acceptable approach that would support DOE's uses of tectonic models in assessing repository performance.

21.7.3. Example of Regulatory Uncertainty Reduction by Rulemaking: Identifying Anticipated Processes and Events and Unanticipated Processes and Events

As defined within 10 CFR 60, the terms "anticipated processes and events" and "unanticipated processes and events" are two categories of processes and events which could occur within the "geologic setting" during the period after permanent closure of the geologic repository. Determination of these categories of processes and events is required by DOE because:

(1) "Anticipated processes and events" are the primary design basis processes and events for the design and analysis of the waste package and engineered barrier system, and

(2) "Anticipated processes and events" together with "unanticipated processes and events" are to form the basis for analysis to determine compliance with the overall system performance objective.

Therefore, the design and analyses of the Waste Package and Engineer Barrier System and determination of compliance with the overall system performance objective cannot be evaluated until the "anticipated processes and events" and "unanticipated processes and events" have been determined.

An important concept which must be understood is that the purpose of the rulemaking on anticipated processes and events and unanticipated processes and events is to define those processes and events which must be considered in the analysis, not to define how the analysis will be conducted or how the decision on the acceptability of the site will be determined. By the same token, there are certain assumptions, such as the format of the final EPA standard which are being made while this rulemaking is progressing.

While the rulemaking deals with both anticipated processes and events and unanticipated processes and events, for purposes of this paper we will only be discussing anticipated processes and events.

The present 10 CFR 60 definition of anticipated processes and events is as follows:

> "Anticipated processes and events means those natural processes and events that are reasonably likely to occur during the period the intended performance objective must be achieved. To the extent reasonable in the light of the geologic record, it shall be assumed that those processes operating in the geologic setting during the Quaternary Period continue to operate but with the perturbations caused by the presence of emplaced radioactive waste superimposed thereon."

The primary area of regulatory uncertainty for this definition lies within the phrase "reasonably likely to occur." This phrase is qualitative and subject to a wide range of interpretations; therefore, unless it is better defined early in the program, there is a possibility of a misunderstanding being propagated during the licensing process which could be costly in both time and effort. Of more immediate concern, however, is that the Yucca Mountain site is undergoing site characterization and the NRC wishes to assure that this program will obtain sufficient information so that significant processes and events can be addressed promptly during licensing. The proposed rulemaking is attempting to make the rule more prescriptive so that misunderstanding and disagreements can be constrained.

The philosophy behind the rulemaking for anticipated processes and events is relatively simple. The NRC considers tbat a reasonably likely processes -- an anticipated process -- is that which approximates a reasonable projection of processes during the period of regulatory concern. In order to make this projection the NRC also considers that the Quaternary record of the region around the site, with emphasis on the Holocene, should provide the primary basis for this projection. When considering the events which go along with this concept, the NRC is of the opinion that, unless there is geologic evidence to the contrary, a reasonably likely event is one which approximates a recurrence of the Quaternary event. For example, in the area of Yucca Mountain, there are faults which have a history of Quaternary movement. Unless there is geologic evidence to the contrary the NRC considers that a reasonably likely event is movement on those faults similar to the movement which occurred during the Quaternary. The NRC also considers that the effects from waste emplacement and reasonably likely human-induced events not under the control of the DOE, such as climatic change due to the introduction of pollutants into the atmosphere, must be factored into the evaluation.

In modifying the rule, the NRC is attempting to assure that the language is clear, concise and free of ambiguities and does not arbitrarily constrain the gathering of scientific information needed for the determination of what the final processes and events will be. For example, the proposed wording for anticipated processes and events is as follows:

> "*anticipated processes and events*" are natural processes and events that may occur in the geologic setting during the period following permanent closure and that have the following characteristics:
>
> (a) '*anticipated processes*' are described by a conservative projection of the average rate of the process under consideration based on an analysis of the nature and rate of the process during the Quaternary Period and consideration of the spatial and temporal variability of the process.
>
> (b) '*anticipated events*' are events similar in characteristics to events which occurred during the Quaternary Period. Such events should be assumed to occur at locations controlled by, or which evolve from, processes and mechanisms which controlled the Quaternary event. The characteristics of an event warrant such modification.
>
> '*anticipated processes and events*' must take into account the perturbations caused by the presence of emplaced radioactive waste, as well as, ongoing and expected human activities that have modified, or are capable of modifying, the geologic setting.

The NRC considers the proposed rule modifiation to be a significant clarification of its intent.

21.8. Conclusion

The NRC is required to make a decision on construction authorization based principally on its determination that there is reasonable assurance that radioactive materials can be received, possessed and disposed of in a geologic repository operations areas without unreasonable risk to public health and safety. NRC is required to make the decision within three years after receipt of the application. An application that is complete and defensible is a prerequisite for NRC's timely decision.

Early NRC identification of geoscience uncertainties at the Yucca Mountain candidate site and working with DOE toward their resolution should contribute to the successful completion of that mission and perhaps lead to the ultimate objective: ensuring that, in this first-of-a-kind waste disposal program, the job is done right the first time.

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Chapter 22

An Overview of the Waste Management Programmes of the OECD Nuclear Energy Agency

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22.1. Abstract

The OECD Nuclear Energy Agency (NEA) has always given priority to safety-and regulatory activities in general and to radioactive waste management and disposal in particular. The Agency's radioactive waste management programmes are conducted under the guidance of the NEA Radioactive Waste Management Committee (RWMC). The two principal Advisory Groups to the RWMC since 1985 have been the Performance Assessment Advisory Group (PAAG) and the Advisory Group on In Situ Research and Investigations for Geological Disposal (ISAG). Meetings of the RWMC and its advisory groups provide unique fora for senior-level representatives from OECD member countries who are responsible for national radioactive waste management policy, regulation, and programme implementation to discuss and exchange information - in an international context - concerning key issues of broad interest in these areas. In addition, the NEA sponsors a multifaceted suite of operational waste management programmes, currently focussed on developing comprehensive and integrated methodologies to assess the long-term safety of radioactive waste disposal systems and increasing confidence in their application and results. The RWMC, through PAAG, promotes information exchange and joint activities concerning the elaboration and use of assessment methodologies in the areas of scenario development, model development, data acquisition, and regulatory requirements. Under PAAG, an Expert Group on Geochemical Modelling and Data supervises the NEA's work in this field, notably the progress and development of sorption and thermochemical data bases for use in geochemical modelling (e.g., radionuclide transport calculations). Also under PAAG, a Probabilistic System Assessment Code (PSAC) User Group helps co-ordinate the development of such codes for radioactive waste disposal applications. Finally, PAAG has established a Working Group on Scenario Identification and Selection to focus discussion internationally on scenario development methodologies for the performance assessment of radioactive waste disposal systems.

The NEA also sponsors international research and development projects, such as the Stripa Project in Sweden (under the auspices of ISAG) and the Alligator Rivers Natural Analogue Project in Australia (under the auspices of PAAG). In addition, the RWMC, through ISAG, co-ordinates activities of NEA member countries involving in situ research and investigations, and ensures that working links are maintained at an international level between performance assessment projects, field projects, and underground research laboratories. Through the exchange of policy, regulatory and scientific and technical information, the establishment of data bases, the promotion of model and code development, the sponsoring of international experimental projects, the organisation of technical symposia, workshops and working groups, and the publication of state-of-the-art reports in selected areas, the NEA seeks to increase scientific understanding and to enhance confidence in the quality of the safety analyses upon which the acceptability of nuclear waste disposal is judged.

22.2. Introduction

The OECD Nuclear Energy Agency (NEA) was established in 1957 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972 when Japan became its first non-European full Member. NEA membership today consists of all European member countries of the OECD, as well as Australia, Canada, Japan, and the United States. The general aim of the NEA is to further the development of the peaceful uses of nuclear energy by sponsoring economic, technical, and scientific studies and projects, and by increasing the compatibility of the safety and regulatory policies and practices of its member countries. Both the International Atomic Energy Agency (IAEA) and the Commission of the European Communities (CEC) have complementary international programmes to those of the NEA, and the CEC is an active participant in several of the NEA's programmes.

The NEA has always been concerned with radioactive waste management and disposal issues and, in the last 15 years, the topic of waste disposal has developed into a priority area for the Agency. The Agency's programme in this area is conducted under the guidance of the NEA Radioactive Waste Management Committee (RWMC), a standing Committee established in 1975 and composed of senior experts and governmental representatives from the agencies and organisations in OECD member countries that are responsible for national waste management policy, regulation, and programme development and implementation. The RWMC provides a unique international forum in the field of radioactive waste management for this grouping of individuals, holding key positions within their own countries, to discuss and - where appropriate and possible - establish consensus on radioactive waste management policy, regulatory, and scientific and technical issues of broad interest to OECD member countries. Principal objectives of the RWMC are:

(1) to improve the general level of understanding of waste management issues and strategies, particularly with regard to waste disposal, and to establish international consensus on specific issues where appropriate and possible,

(2) to assist NEA member countries with the development of methodologies to assess the long-term safety of radioactive waste disposal systems, and

(3) to increase confidence in the application and results of these methodologies.

In the 1970's, the RWMC established specialised sub-Groups, in particular the Co-ordinating Group on Geological Disposal (CGGD) and the Seabed Working Group (SWG), which were instrumental in promoting international initiatives and consensus in their respective areas of competence. For example, a large international research and development (RLD) programme to investigate the safety and engineering feasibility of seabed disposal of high-level wastes was launched in 1977, the International Stripa Project was established in 1980 to investigate the potential of fractured hard rock for radioactive waste isolation, and a state-of-the-art review of geological disposal was published in co-operation with the CEC in 1984.[1] In 1985, given the increasing international emphasis on long-term safety studies for waste disposal, the CGGD was replaced by two new principal Advisory Groups to the RWMC, one on Performance Assessment (PAAG), the second on In Situ Research and Investigations for Geological Disposal (ISAG).

The NEA sponsors a multifaceted programme in the area of waste disposal that currently consists of six different types of activity:

(1) As mentioned above, the discussion and exchange of information concerning national policies, programmes and regulations on the management and disposal of radioactive wastes, and the promotion of integrated approaches, particularly with regard to the performance assessment of waste disposal systems,

(2) The establishment of geochemical data bases (i.e. , the Sorption Data Base and the Thermochemical Data Base),

(3) The promotion of model and code development, and benchmarking, verification and validation exercises (i.e., the Probabilistic System Assessment Code User Group and the HYDROCOIN and INTRAVAL Projects),

(4) The sponsoring of international experimental projects (i.e., the Stripa Project and the Alligator Rivers Natural Analogue Project),

(5) The organisation of symposia, workshops, working groups, and courses on selected topical subjects (e.g., symposia on safety assessment and on the Stripa Project, a working group on the identification and selection of scenarios, workshops on human intrusion, on excavation effects, and on sealing of repositories, etc.), and

(6) The publication of a nuclear waste bulletin, state-of-the-art reports, and workshop and symposia proceedings.

The NEA is able to provide the international framework and organisation for such activities. The actual activities undertaken or supported must be approved by the RWMC, and they are generally characterised by generic aspects of high-priority interest to many (if not all) member countries. The remainder of this paper will provide a broad overview of the NEA's current radioactive waste management activities in the six areas outlined above.

22.3. Performance Assessment of Waste Disposal Systems

As noted in the Introduction, the NEA's programme in the field of performance assessment of radioactive waste repositories is co-ordinated by PAAG, which provides an international forum for the discussion of relevant issues, notably those associated with establishing confidence within the technical community on the reliability of methodologies for conducting long-term (postclosure) performance assessments. Specifically, PAAG provides a framework for the exchange of information and experience aimed at furthering the development of these methodologies and avoiding unnecessary duplication of effort between different national programmes. In addition, PAAG advises the RWMC on scientific and technical aspects of performance assessment and assists the RWMC in the development and co-ordination of performance assessment activities, focussing on issues associated with scenario development, model development, data acquisition, and regulatory requirements. PAAG has a particularly important role to play as concerns the identification of future research priorities and the promotion of comprehensive and integrated approaches to performance assessment. It is PAAG's role to keep all of the component elements of a system's performance assessment in perspective, and to discuss and understand the varying levels of attention that may be given to individual elements in the member countries, all the while promoting the coherent integration of these elements. PAAG's current activities fall into all six of the areas mentioned in the Introduction.

22.3.1. Geochemical Data Bases

Under PAAG, an Expert Group on Geochemical Modelling and Data supervises the NEA's work in this field, notably the progress and development of sorption and thermochemical data bases for use in geochemical modelling (e.g., radionuclide transport calculations). By promoting the development of such data bases, the NEA is attempting to provide the primary geochemical modelling data needed to assess the performance of radioactive waste disposal systems.

22.3.2. NEA Sorption Data Base (SDB) Project

The objective of the SDB Project is to compile experimental data on the sorption of different radionuclides under various geochemical conditions. About 11,000 empirically determined sorption coefficients (Kd's) with corresponding experimental-condition parameters are currently available for a large suite of key radionuclides and solid and liquid phases. For example, Cs, Sr, Am, Np, Se and I are represented in the data base, and data exists for granitic rock types, common fracture-filling materials, and various clay minerals. The Project was initiated in 1981, and a final version of the data base is now freely available from the NEA in IBM/PC-compatible format. The data base operates with the dBase III Plus computer program.

22.3.3. NEA Thermochemical Data Base (TDB) Project

The general objective of the TDB Project is to advance the level of understanding and prediction of radionuclide migration through geologic media. The Project, under development at the NEA Data Bank, consists of a compilation of fundamental thermodynamic values. It is intended to make available a comprehensive, internally consistent, and internationally recognised and quality-assured chemical thermodynamic data base of generic application, and meeting in particular modelling requirements for the safety assessment of radioactive waste disposal systems. Compilation of all available experimentally determined thermodynamic data for U, Tc, Np, Pu and Am is being undertaken, and other elements will possibly be considered in future. These data are being critically reviewed internationally and a selected set of "best" data will be provided for each element considered in due course. The compiled data sets are freely available from the NEA Data Bank and the selected data sets will be published separately for each element as work proceeds, most probably starting in late 1989 (for U), and continuing until 1995 or later. Given the level of ambition for this Project from the scientific viewpoint, progress has been relatively slow since its initiation in 1983, and possibilities for accelerating the Project are currently being investigated.

22.3.3.1. Model and Code Development

NEA Probabilistic System Assessment Code (PSAC) User Group

The PSAC User Group was established in 1985 by the RWMC to further the development in member countries of computer codes for the probabilistic safety assessment (PSA) of radioactive waste disposal systems. Such codes simulate the evolution of the entire repository system and provide the framework for a systematic approach to variability and uncertainty in data and parameter values. Because PSA codes are large and are run many times with varying input values of the parameters that describe the disposal system ("stochastic" analyses), such codes must incorporate simplified submodels (e.g., for the repository, geosphere and biosphere) of the disposal system. Activities of the PSAC User Group comprise information exchange, peer review of national code development efforts, joint code development, discussion of topical issues, and verification and benchmarking of codes (called PSACOIN exercises). Issues considered by the Group have included techniques for sensitivity analysis, reduction of research models to PSA submodels, time and spatial dependency and variability, input data acquisition and handling, statistical sampling procedures, and software quality assurance.

The PSACOIN exercises represent an especially important activity of the Group as formal code comparisons can help verify that complex codes developed for safety assessments are functioning as intended. In particular, such international code intercomparison exercises afford the opportunity to participants to identify and correct errors in their codes through the adoption of an iterative approach to implementation of the exercises. Completed exercises include Level 0[2] - a test of the "executive" (or driving) modules of PSA codes - and Level E[3] - a comparison with exact solutions. Intercomparison of a variety of results from the participating codes within these two exercises has indicated that, after correction of errors in a number of codes and final completion of the exercises, nearly all are functioning as intended and meet their design requirements. Three further PSACOIN exercises are in progress: Level 1a, incorporating a more realistic system model representative of deep geological disposal concepts, Level 1b, incorporating a more detailed biosphere submodel, and Level 2, focussing on different techniques for sensitivity analysis. Technical support with regard to statistical analyses of results from PSACOIN exercises and code compilation and exchange is provided by the NEA Data Bank.

22.3.4. HYDROCOIN and INTRAVAL Projects

The HYDROCOIN and INTRAVAL Projects are international computer modelling exercises focussed on groundwater flow and radionuclide transport, established and managed by the Swedish Nuclear Power Inspectorate (SKI), with the participation of the NEA in the Project Secretariat.

The HYDROCOIN Project is completed and the Level 1 final report on groundwater hydrology code verification was published by the NEA in 1988,[4] with the Level 2 (validation) and Level 3 (uncertainty and sensitivity analysis) reports scheduled to be published in 1990. Following difficulties experienced in the HYDROCOIN Project as concerns validation, the INTRAVAL Project has as its objective an evaluation of the validity of radionuclide migration models. Interaction between model developers and experimentalists is being stressed, and a test-case approach using laboratory- and field-scale experiments, as well as natural analogues, has been adopted. In addition, the development of a conceptual framework for model validation features strongly in the Project. The Project was initiated for a three-year first phase (1987-1990), with extension for a three-year second phase possible should results from the first phase warrant this.

22.3.4.1. International Experimental Projects

Alligator Rivers Natural Analogue Project (ARAP)

ARAP is sponsored by the NEA and separately financed for a three-year period (1987-1990) by Australia, Japan, Sweden, the United Kingdom, and the United States. The Project is managed by the Australian Nuclear Science and Technology Organisation (ANSTO), and has as its objective furthering understanding of the long-term chemical and physical processes likely to influence the transport of radionuclides through geological environments. The geochemistry and hydrogeology of the Koongarra uranium-ore deposit in the Alligator Rivers region of the Northern Territory, Australia, are being studied in detail in the field, in the laboratory, and through modelling. Extensive geological, geochemical and hydrological data for the ore formation, previously collected for exploration purposes, showed that the uranium in the near-surface weathered zone of the formation had been mobilised and dispersed in the direction of groundwater movement. Project participants are attempting in particular to obtain an understanding and description of the migration of uranium and its decay products away from the ore body. It has been found that the radionuclides have moved only a few tens of metres away from the weathered zone over a period of several million years, and that no detectable movement of radionuclides has occurred in the undisturbed deeper layer of the ore body.

22.3.4.2. Symposia, Workshops, Working Groups and Courses

NEA Working Group on Scenario Identification and Selection

PAAG established an ad hoc Working Group on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal in 1987 with the purpose of discussing, evaluating and elaborating systematic methodologies for the development of potential radionuclide release scenarios (possible evolutions) to be considered in assessing the long-term safety of waste disposal systems. The work of this Group has benefitted greatly by the earlier work in this area carried out by Sandia National Laboratories (USA) under contract to the U.S. Nuclear Regulatory Commission.[5] The Working Group has prepared a draft report, and it is expected that a final report describing the state-of-the-art in this field will be ready for publication in early 1990. Preliminary conclusions and recommendations of the Group are as follows:

(1) Representative scenarios for use in consequence analyses must be chosen using a systematic, tractable and transparent methodology,

(2) Well-defined criteria should be used to eliminate unimportant scenarios prior to undertaking detailed consequence analyses,

(3) Each step of the scenario development procedure should be clearly documented to ensure that the reasons for arising at a final set of representative scenarios for analysis are both traceable and comprehensible,

(4) Groups outside the radioactive waste disposal field should be involved in scenario development, for example by reviewing lists of potentially relevant events, features and processes,

(5) Feedback from consequence analysts (modellers) and an iterative approach to scenario development are required, and

(6) Early interaction should be promoted between those involved in scenario development and those involved in model development and data collection activities for particular scenarios, as well as with those involved in research, site selection and characterisation, and repository design activities.

Workshop on Human Intrusion

PAAG organised a Workshop on the Role of Human Actions in Performance Assessment of Radioactive Waste Disposal Facilities on 5th-7th June 1989. The Workshop focussed on the treatment, in safety assessments, of potential human intrusive actions at waste disposal sites. Possible technical and administrative measures designed to reduce the probability or consequence of human intrusion were also discussed. A principal conclusion from this Workshop was that a proper balance needs to be retained between the effort expended on evaluation of the likelihood and effects of human intrusion, versus the effort expended on the calculation of doses and their likelihood of arising through the transport by groundwater of radionuclides to man's environment during "undisturbed" repository performance. Growing national experience in the area of human-intrusion assessment is indicating that in many cases human-intrusion scenarios may be the dominant contributor to risk. Proceedings of the Workshop will be published by the NEA in late 1989.

Symposium on Safety Assessment

PAAG, in co-operation with the CEC and the IAEA, is organising an International Symposium on the Safety Assessment of Radioactive Waste Repositories, to be held in Paris on 9th-13th October 1989. The Symposium will focus on the approaches and methodologies being used for assessing the postclosure safety of different disposal concepts for various types of radioactive waste, and on the results of safety studies in repository development programmes. The conclusions arising from this Symposium will be carefully studied by the PAAG and RWMC, and will constitute the basis for future developments within the NEA in this field. In this regard, the NEA Secretariat is planning to prepare a "Collective Opinion" for approval by the PAAG and RWMC, representing a consensus statement on developments in the area of performance assessment over the past decade, and pointing toward issues on which more R&D emphasis may be needed in future. In addition, Symposium Proceedings will be published by the NEA in 1990.

Courses

The NEA Data Bank is organising a series of courses on the use of well-known geochemical modelling codes. Courses have been held on the use of the PHREEQE (twice) and MINEQL-EIR codes, and the next course, tentatively scheduled to be held in September 1989, will deal with the EQ3/6 code.

22.4. In Situ Research on Land Disposal

As noted in the Introduction, the NEA's programme in the area of in situ research and investigations for geological disposal is co-ordinated by ISAG, which provides an international forum for the discussion and co-ordination of site-specific R&D programmes in this area. Specifically, ISAG provides a framework for the exchange of information between different field projects and underground research laboratories, fosters liaison between field projects and performance assessment projects at an international level, examines problems of mutual concern among in situ research and demonstration projects, and advises the RWMC in its area of competence. Important underground research and demonstration laboratories represented within ISAG include the Stripa Mine (Sweden), the Grimsel Test Site (Switzerland), the Underground Research Laboratory (Canada), Mol (Belgium), the Asse Mine (Federal Republic of Germany) and the Waste Isolation Pilot Plant - WIPP (United States). Important field projects in which potential disposal sites are being investigated in situ include Yucca Mountain and WIPP (United States), and Konrad and Gorleben (Federal Republic of Germany).

An initial activity of ISAG was the preparation of a report, published by the NEA in 1988, that documented the status of in situ research and investigation programmes in OECD member countries.[6] This report noted the fundamental and essential character of such programmes for geological disposal concept assessment, site selection and characterisation, and repository development. The report includes a broad description of each national institutional framework and approach to disposal. On the basis of this report and its own review of policies for waste disposal, the RWMC, in a Preface to the report, reaffirmed its confidence in the safety and feasibility of geological disposal of radioactive wastes, and strongly recommended the further active pursuit of in situ research and investigation programmes in OECD member countries.

22.4.1. International Experimental Projects

22.4.1.1. International Stripa Project

The International Stripa Project was launched in 1980 under NEA auspices on the strength of the results achieved under the Swedish-American Co-operative Programme, which was initiated in 1977 at the disused Stripa iron-ore mine in Sweden, with the aim of studying the potential of fractured hard rock for the isolation of radioactive wastes. The Project, managed by the Swedish Nuclear Fuel and Waste Management Company (SKB), has developed in three phases since then, with Phase 3 work having commenced in 1986 and due to be completed in 1991. Work in the first two phases concentrated on hydrogeological and hydrochemical investigations of the Stripa granite, migration experiments, fracture-zone studies, and the behaviour of bentonite as a backfilling and sealing material. The third (and final) phase builds upon the results obtained in the previous two phases, and consists of programmes in two major areas:

(1) Fracture flow and radionuclide transport, including model validation and the development of site assessment methods and strategies, and

(2) Groundwater flow-path sealing, including the identification, selection, evaluation, and demonstration of appropriate sealing materials and techniques.

Although in situ work within the Stripa Project is carried out in a fractured granite formation, it is considered that the methods used and some of the results obtained are applicable to repository development programmes focussing on other geologic media. The Stripa Project is separately financed, with the third phase including the participation of seven countries: Canada, Finland, Japan, Sweden, Switzerland, the United Kingdom, and the United States.

Progress in Phase 3 has recently been made toward investigating a previously "undisturbed" fractured granitic rock volume, and developing and validating conceptual and mathematical models for groundwater flow through this rock volume. In addition, developmental work has advanced on several in situ investigation technologies, including seismic, radar, and hydraulic instrumentation. Finally, the properties of different materials for injection grouting have been studied, and plans laid for several in situ large-scale grouting tests.

22.4.2. Symposia and Workshops

22.4.2.1. Workshops on Excavation Effects and Sealing

At its first meeting, ISAG highlighted the topics of excavation effects and of backfilling and sealing as being of sufficient priority and international interest to merit the organisation of specialist workshops to address them in detail. Subsequently, a first Workshop on Excavation Response in Geological Repositories for Radioactive Waste was held in Winnipeg, Canada, on 26th-28th April 1988[7], and a follow-up Workshop (organised jointly with the CEC) on the Sealing of Radioactive Waste Repositories was held in Braunschweig, Federal Republic of Germany, on 22nd-25th May 1989.[8] The first Workshop examined the geomechanical and hydrological response in surrounding rock masses of excavation-induced damage, and the implications for the design and safety of radioactive waste repositories. The second Workshop reviewed the progress of in situ investigations of repository sealing technology for boreholes, shafts, drifts, fractures and disturbed zones, and identified issues requiring further investigation to support either repository design programmes or postclosure performance assessments. The results of both of these Workshops pointed strongly to the need in most of the participating countries for increased interaction between and integration of (i) system performance assessment programmes and (ii) in situ research and investigation programmes concerned with the extent and effects of excavation damage and the development of repository sealing technology. With few exceptions, it was generally unclear from the Workshops what role system assessment considerations played in the design and development of the in situ research and investigation programmes in the two areas addressed by the Workshops.

22.4.2.2. Stripa Project Symposium

In cooperation with SKB, ISAG is organising an International Symposium on the Stripa Project ("In Situ Experiments Associated with the Disposal of Radioactive Waste"), to be held in Stockholm, Sweden, on 3rd-4th October 1989. The broad objectives of this Symposium are to summarise results and conclusions from Phase 2 of the Project and to review early results and future plans for Phase 3. Symposium Proceedings will be published by the NEA in 1990. In addition to this Symposium, several Workshops concerned in detail with particular aspects of the Project are held each year, but these Workshops are only open to participants from the seven countries that are supporting Phase 3 work.

22.4.2.3. GEOVAL-90 Symposium

In concert with PAAG, ISAG is extremely interested in the validation of models used for assessing the performance of geologic disposal systems and, in particular, is focussing on the role of in situ investigations in model validation. The NEA is therefore cosponsoring the second GEOVAL Symposium on the validation of geosphere flow and transport models - GEOVAL-90 - which is being organised by the SKI and which will be held in Stockholm, Sweden, on 14th-17th May 1990. This Symposium will review recent achievements and planned activities for validation, as well as the conceptual framework for validation strategies in the context of radioactive waste disposal programmes. In particular, the Symposium will highlight the interaction between modelling and experimental programmes, and provide special attention to the validation of coupled geochemical, thermo-hydromechanical, and fracture-flow models.

22.5. Other NEA Waste Management Activities

22.5.1. Seabed Disposal of High-Level Radioactive Waste

A Co-ordinated Programme on Seabed Disposal of High-Level Radioactive Waste was formally created within the NEA in 1977, and a decade-long international research effort was initiated under the direction of the NEA Seabed Working Group (SWG). The research effort sought to answer three key questions:

(1) Are there locations under the oceans which have the geological stability and barrier properties suitable for disposal?

(2) Is it possible to implant waste-filled canisters in the seabed sediments and what effect does this emplacement have on the barrier properties of the containment system?

(3) What are the radiological consequences of seabed burial?

An eight-volume series was published by the NEA in late 1988 and early 1989[9] providing an assessment of the technical feasibility and radiological safety of this disposal concept. Volume 1 includes an overview of the research and a summary of the results, and the remaining volumes contain a more detailed description of the radiological assessment, the geoscience characterisation studies, the engineering studies, and the scientific basis upon which the radiological assessment is built.

The study resulted in specific conclusions with regard to the three key questions above. Among these were the following:

(1) Sites have been found in both the North Atlantic and North Pacific Oceans which, based on current guidelines and available data, appear suitable for disposal.

(2) Both "penetrator" and drilled emplacement of waste canisters in sediment formations are possible using currently available technology, and both are economically feasible.

(3) The primary sediment barrier would contain most of the radionuclides for thousands of years, and any possible subsequent release of radionuclides to man's environment would result in radiological risks many orders of magnitude below current standards for the protection of human health, even in the long term.

The SWG recommended, however, that further research would be necessary to reduce uncertainties on a number of specific issues, related in particular to engineering and to the migration of radionuclides in the sediments, before any attempt is made to use seabed disposal for high-level radioactive wastes. Nonetheless, because disposal in deep geological formations on land is currently the preferred option for high-level wastes in all OECD member countries, only a limited effort will be devoted by the RWMC to seabed disposal in the near future; this effort will serve essentially to maintain contact between the various groups in OECD member countries still interested in this disposal concept.

22.5.2. Dumping of Low-Level Radioactive Wastes into the Sea

Sea dumping of low-level radioactive wastes has not been practiced since 1982 in response to discussions on this matter by the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the "London Dumping Convention"). This option for the disposal of low-level wastes is, nonetheless, being kept open by several OECD member countries, and important scientific data and results continue to be accumulated on the processes controlling radionuclide transport and dispersion in the sea through the NEA Co-ordinated Research and Environmental Surveillance Programme (CRESP) for the Atlantic dumping site, initiated in 1981. CRESP is also concerned with coastal discharges of radioactive wastes, and the distribution of radioactive waste materials within the marine environment in the Paris Commission area - a limited area of the northeastern Atlantic Ocean. CRESP research activities focus in particular on geochemistry and physical oceanography, biology, the mathematical modelling of radionuclide transport to marine biota and to man, and radiological surveillance and assessment. CRESP will continue in its current phase until 1990, at which time a decision will be taken with regard to the possible extension of the Programme. In the meantime, the NEA intends to publish a third volume of summary findings concerning an interim oceanographic description of the Atlantic dumping site.[10] CRESP activities are conducted within the framework of the OECD Multilateral Consultation and Surveillance Mechanism for Sea Dumping of Radioactive Waste, adopted by OECD member countries in 1977 in order to reinforce the provisions of the London Dumping Convention.

22.5.2.1. Decommissioning of Nuclear Plants

In 1985, the RWMC established a Co-operative Programme on the Exchange of Scientific and Technical Information Concerning Nuclear Installation Decommissioning Projects. The objectives of this Programme are to provide a forum for the exchange of scientific and technical information concerning decommissioning, and to develop the operational experience and data base needed for the future decommissioning of large nuclear power plants. Fifteen national decommissioning projects in 10 OECD Member countries currently participate in the Programme.

22.5.2.2. NEA Nuclear Waste Bulletin

The NEA prepares and publishes about once every nine months a Bulletin highlighting recent progress within national and international radioactive waste management activities, policies and programmes.[11] Detailed information and updates on NEA waste management activities are regularly included, as are recent developments in a variety of areas contributing to the development of acceptable technologies for the management and disposal of radioactive wastes (e.g., performance assessment, in situ investigations, repository engineering, scientific data bases, regulatory developments, etc.). The Bulletin is available free-of-charge to interested members of the waste management community, and the next issue (No. 4) is scheduled for publication in September 1989.

22.6. General Discussion

It will be clear from the preceding overview that the large majority of the NEA's current waste management activities address one or more of the principal technical uncertainties in long-term (postclosure) performance assessments of waste disposal systems. Such uncertainties can be considered to arise from three sources: (i) uncertainty in the evolution of disposal systems (scenario uncertainty), (ii) uncertainty in the predictive models used to simulate possible evolution of the disposal system and to assess scenario consequences, and (iii) uncertainty in the data and parameters used in the modelling programme. At a general level, a number of lessons have been learned through NEA international co-operative programmes aimed at the reduction and characterisation of technical uncertainties, and several of these are noted here:

(1) Approaches to the treatment of uncertainty should be systematic, documentable and repeatable. The transparency of a safety case is an essential part of its presentation. These are important points in the discussion on development of safety assessment methodologies within NEA programmes (e.g., the working group on scenarios).

(2) Multiple approaches, as well as multidisciplinary approaches are needed to the treatment of technical uncertainty in postclosure performance assessments. A combination of laboratory, field, in situ and analogue data will have to be relied upon. Both probabilistic and deterministic modelling may have a role to play. Such concepts are underlying themes of many of the NEA's waste management activities.

(3) Time and again, the need for early and ongoing collaboration and interaction between experimentalists and performance assessors, and for an integrated and iterative approach to site characterisation and performance assessment have been stressed in the context of NEA programmes and meetings. With certain exceptions, it still appears that insufficient attention is given to this type of collaboration, interaction and integration in many national waste disposal programmes.

(4) Even though real data should be relied on to the extent possible in safety assessments, the long times over which the safety of disposal systems must be ensured means that the formal use of expert judgement and peer review will play an important part in establishing confidence in these assessments. Criteria for the use of such human judgement need to be clearly articulated, and possible bias or uncertainties associated with the use of such judgement need to be defined. This important area has apparently received relatively little attention to date.

(5) Technology transfer from other areas may help to avoid unnecessary duplication of effort in the waste disposal area. For example, the use of statistical techniques developed for PSA in other areas may be of use in waste disposal applications of PSA.

(6) Notwithstanding the previous comment, the development of new techniques and the extension or refinement of existing techniques will be necessary, and are being undertaken in many NEA programmes, in order to reach the required level of assurance in safety assessments. It should be noted that such "techniques" include both the component tools and techniques for conducting system performance assessments, and the instrumentation and measurement techniques for in situ, field and laboratory investigations of potential repository sites.

(7) Finally, it is important to stress that the RWMC as a whole already stated several years ago: (i) that a sufficient level of technical understanding and development had been reached for detailed short- and long-term safety assessments of geological disposal systems to be feasible, and (ii) that current safety requirements and criteria can most likely be met with currently available technology and at reasonable cost.[12] In addition, the RWMC has more recently stated that it is now appropriate to place increasing emphasis on the development of underground research laboratories, both at potential repository locations and at demonstration sites, and emphasis on this area is indeed increasing.[6]

The progress and maturity of work in this field are demonstrated by the increasing level of consensus within OECD member countries on the general methods adopted for demonstrating and evaluating the safety of radioactive waste disposal systems. The international framework provided by the RWMC and its various subgroups has played and will continue to play an important role in focussing international efforts and discussion on those policy, regulatory and technical issues of key importance and wide interest to the member countries.

22.7. Concluding Summary

The NEA since its inception has been concerned with the issue of radioactive waste management and, in the last 15 years, the topic of waste disposal has developed into a priority area for the Agency. The programme is conducted under the guidance of the NEA Radioactive Waste Management Committee, a standing Committee composed of senior experts and governmental representatives responsible for national waste management policy, regulation, and programme implementation. The NEA's principal role in this area currently is to assist its member countries with the development of comprehensive and integrated methodologies to assess the long-term (postclosure) safety of radioactive waste disposal systems and to increase confidence in their application and results. This is accomplished through the discussion and exchange of policy, regulatory and technical information and experience among national experts, joint studies of issues important for safety assessment (e.g., scenario development, treatment of uncertainties), and joint development of the computer codes and data bases used to assess the release and transport of radioactive materials to man's environment. The NEA also sponsors international R&D projects, such as the Stripa Project and the Alligator Rivers Analogue Project, and co-ordinates activities of its member countries involving in situ research and investigations.

Finally, the NEA ensures that working links are maintained at an international level between performance assessment projects, field projects, and underground research laboratories, through specialised working groups operating in the Agency's framework. The ultimate purpose of this international effort is to reach the level of scientific understanding required to ensure that nuclear waste disposal systems will be able to contain and isolate the radioactive materials sufficiently well that such repositories will not cause any harm to man or his environment either now or in the future. Such international co-operative programmes are also aimed at enhancing the quality of the safety analyses upon which the acceptability of nuclear waste disposal is judged.

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Chapter 23

The CEC Action in the Field of Geological Disposal: An Overview

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23.1. Abstract

A substantial part of the R&D Community programmes on radioactive waste management and storage has been devoted for many years to geological disposal studies. This paper presents an overview of salient achievements in this field covering "basic" research in support of the development of repositories and pilot/ demonstration facilities.

The cooperative aspect of these activities is emphasized, as well as their significance and contribution to safety assessment studies. It is anticipated that, in the near future, these lines of actions will have to be pursued increasingly with a view to the public acceptance of the geological disposal concept.

23.2. Introduction

For nearly 15 years, the Commission of the European Communities (CEC) has been implementing and supporting research and development programmes on radioactive waste management and storage. This action mainly takes the form of cost-sharinq contracts concluded between the CEC and competent organizations in the member-states; this financial support, together with the pooling of resources and expertise, ensures better coordination and avoids duplications of effort at the Community level. The overall coherence of these actions is ensured by a 10-year Community Plan of Action in the field of radioactive waste (1980-1992).

Contributing to safety assessment studies, waste treatment and waste form characterization, together with geological disposal, were and still are the main components of these programmes. This does not mean, however, that administrative and regulatory aspects were neglected. It is the purpose of the present paper to focus on salient achievements of the geological disposal studies.

The first Community programme (1975-1979) was mainly concerned with problem identification (e.g. repository design studies, assessment of the admissible thermal loading in geological formations), collection of basic data and a survey of geological formations potentially suitable for disposal in the European Community (EC).[1] For the sake of efficiency, the work was focused on three typical host media: salt, clays and hard rock (granite).

During the second programme (1980-1984), research was carried out under the following broad items: site exploration and characterization, technology of disposal (including engineered barriers), radionuclide migration in the geosphere, and safety assessment of disposal. Together with the Joint Research Centre (JRC) at Ispra (Italy), a section of the programme was also devoted to disposal into the seabed, as a contribution to the OECD-NEA Seabed Working Group.[2] The amount of laboratory and in-situ work (deep boreholes and underground laboratories) increased considerably; at the same time, several truly coordinated projects were launched, e.g. MIRAGE and PAGIS (see below).[3]

Given the encouraging results obtained in favour of the deep geological disposal concept,[4] the third programme (1985-1989) was organized around the same lines, with the notable addition of CEC support and participation in the design, construction and operation of underground pilot/demonstration facilities, operated by national bodies of the member-states, and under the provision that they will be open to joint Community participation (see Table 23.1).

The main activities and results of this programme, concerning geological disposal, will be

Table 23.1. Organization of the third CEC radioactive waste programme (1985-1989). (Sections dealing with geological disposal are in bold type.)

PART A: Waste Management Studies and Associated R&D Action	
Task 1	System studies
Task 2	Improvement of waste treatment and conditioning technologies
Task 3	Evaluation of conditioned waste and qualification of engineered barriers
Task 4	**Research in support of the development of disposal facilities: shallow burial and geological disposal studies**
Task 5	**Safety of geological disposal**
Task 6	Joint elaboration of radioactive waste management policies
PART B: Pilot/Demonstration Underground Facilities	
Project 1	**HAW - Pilot underground facility in the Asse salt mine** (FRG)
Project 2	**HADES - Pilot underground facility in the Boom clay at Mol** (B)

presented in the following. Details on other aspects of waste management (treatment, conditioning, cost evaluation, quality assurance, regulatory aspects, etc.) can be found elsewhere.[5] Note that the complete list of contract reports is regularly updated in the information bulletin "EC-FOCUS" published by the programme.

23.3. Research in Support of the Development of Underground Repositories

In the 1985-1989 programme, this aspect was covered by Task 4 (see Table 23.1). Given the results obtained in the previous programme and the evolution of knowledge all around the world, the emphasis in this task was put on specific research items in which coordinated projects could be set up. Some of these were continuations of projects already started in the second programme. The research items were: study of sites and their characterization, engineered barriers and repository design, migration of radionuclides in the geosphere, and shallow land burial. Research on sea bed disposal was discontinued.

International co-operation was maintained and enlarged in these research items. The growing implication of Third Countries having cooperative agreements with the CEC in the field of radioactive waste management (Canada, Sweden, Switzerland, United States) was a noteworthy feature of this third programme.

Abbreviations and/or acronyms for most of the CEC contract partners are given in Table 23.2.

23.3.1. Site Characterization

23.3.1.1. General Survey of Geological Formations and Development of Measurement Techniques

This research item aims at developing and improving adequate techniques for measuring relevant properties of geological formations. At the same time, these techniques are applied to large-scale and in-situ characterization of these formations.

For granite, attention was paid to the detection of fractures using borehole electric and electromagnetic probes (BRGM). The characterization of groundwater geochemistry, mainly the lanthanide content, was the subject of the downhole geochemical probe CHROMATO (CEA).

The salt formation in the ASSE salt mine, representative of North-German salt domes, was investigated by deep dry-drilled boreholes in which geomechanical measurements, as well as the analysis of fluids and gases liberated during drilling, were carried out (ECN and GSF). In parallel, suitable geohydrological surveying methods for aquifers near salt domes were reviewed (RIVM).

Table 23.2. Main abbreviations for CEC contract partners

ANDRA	Agence nationale pour la gestion des dechets radioactifs, Paris (F)
ATKINS	Atkins Engineering Sciences, Epsom, Surrey (UK)
BGS	British Geological Survey, Nottingham (UK)
BRGM	Bureau de recherches geologiques et minieres, Orleans (F)
BULLEN	Bullen and partners, consulting Engineers, Croydon (UK)
CEA	Commissariat à l'énergie atomique, Paris (F)
ECN	Energieonderzoek Centrum Nederland, Petten (NL)
ENEA	Comitato nazionale per la ricerca e per lo sviluppo dell'Energia Nucleare e delle Energie Alternative, Roma (I)
ENRESA	Empresa Nacional de Residuos Radiactivos, Madrid (E)
GSF	Gesellischaft fur Strahlen-und Umweltforschung mbH (D)
IOS	Institute for Oceanographic Sciences, Wormley (UK)
ISMES	Istituto Sperimentale Modelli e Strutture. Bergamo and Roma (I)
NRPB	National Radiological Protection Board, Chilton (UK)
OVE ARUP	Ove Arup, London (UK)
RISØ	Risø National Laboratory. Roskilde (DK)
RIVM	National Institute for Public Health, Bilthoven (NL)
SCK/CEN	Studiecentrum voor Kernenergie/Centre d'etude de l'énergie nucléaire, Mol (B)
UKAEA	United Kingdom Atomic Energy Authority (UK)

Finally, the problem of fault detection and characterization in indurated clays, or mudstones, was the subject of a co-operative programme, putting together the efforts of BGS (geophysical and hydrogeological methods), ISMES (geophysical methods) and the University of Exeter (UK) (gas emanation techniques). At the same time, adequate nondestructive methods for sampling deep clays were developed (CEA). An X-ray scanning device mounted in a mobile laboratory, the "X-core system," provides an in-situ method of examining deep rock samples immediately after coring (BRGM).

These work products actually showed that suitable site investigation techniques exist and, when necessary, can be combined in order to fulfill the objectives of site reconnaissance. It is also worthy of mention that the existing European catalogue of geological formations that show suitable features for waste disposal was recently extended to include Spain (ENRESA).

23.3.1.2. Rock Mechanics

The aims of this research program are to improve the understanding of large scale rock mass behaviour through adequate laboratory or in-situ tests and to develop suitable calculational tools to predict this behaviour.

For hard rocks, a large thermo-hydro-mechanical test was conducted in an experimental room of the Fanay-Augeres uranium mine (CEA).

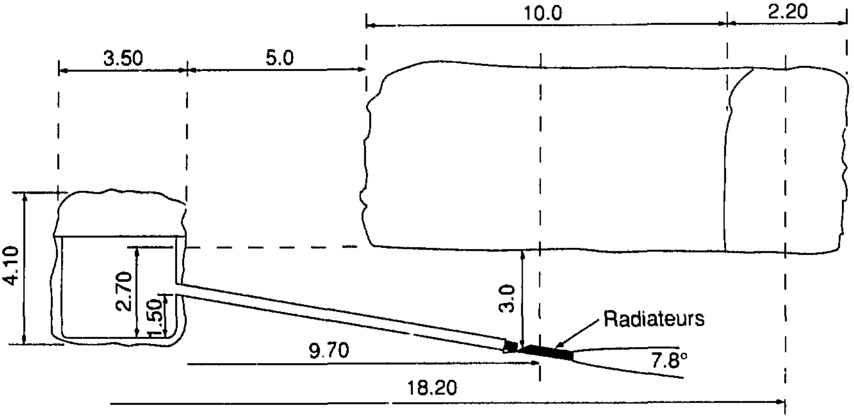


Figure 23.1. The Fanay-Augeres in-situ experiment (CEA). Cross-section through the service gallery and the test room showing the emplacement of the heaters (radiateurs).

As shown in Figure 23.1, heaters were inserted horizontally below the floor of the room so that thermally-induced stresses and displacements, and their influence on the fractures present on the site, can be measured and compared to predictions using computer codes. In parallel, the role of micro-fissuring on the behaviour of granite was investigated in-situ and on rock samples (CEA). Furthermore, the basic mechanisms for fracture initiation and propagation, as well as their consequences for the stability of underground openings, were reviewed (Technical University Delft, NL).

The site of SCK/CEN at Mol, particularly the underground laboratory and pilot facility in the Boom clay at 225m depth, is a major focus for research on the behaviour of plastic clay (Figure 23.2). The in-situ behaviour of this medium under normal and elevated temperature conditions is recorded by the measurement of ground pressures on the lining, pore pressures by piezometers, dilatometer tests, and deformations of the lining (SCK/CEN and ANDRA). Supporting laboratory tests were conducted on hollow, thick cylinders (ANDRA). The fundamental behaviour of heated clays was investigated on samples using a special laboratory testing device, HITEP, and modelled by a coupled thermal, seepage and mechanical computer code (ISMES); this latter research is carried out in co-operation with AECL of Canada. Complementary investigations on the changes in microstructure of heated clays with a view to understand the basic mechanisms governing the overall mechanical behaviour were carried out by CEA. In addition a cross hole geophysical monitoring technique, using the changes in frequency spectrum for sound waves travelling through clays subject to thermal and/or mechanical effects, was developed (ME2i, Paris, F). Finally, in-situ convergence and ground pressure measurements have been carried out in the underground laboratory at Pasquasia in Sicily, in a stiff Pliocene clay (ENEA).

Specific investigations were performed on the rheology of salt, for which an impressive body of results has already been obtained in previous Community programmes. The role of inherent or added brine on the creep behaviour of massive or crushed salt was further investigated by the University of Utrecht (NL). The simulation of the mechanical complex of salt with a sedimentary cover using centrifuge models was continued using a very large centrifuge in which accelerations up to 100g could be obtained (ANDRA).

A major effort on salt was conducted in the second phase of the COSA project, which was designed to validate rock-mechanics computer codes for salt against a well-defined in-situ experiment simulating disposal situations in salt. The

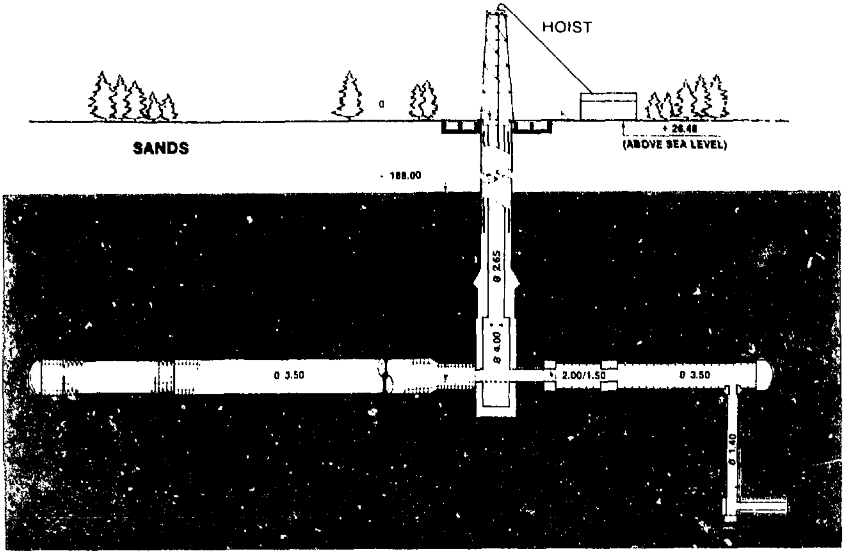


Figure 23.2. The underground works at Mol (SCK/CEN)

case studied was the series of convergence and pressure measurements carried out between 1980 and 1983 in a 300m deep dry-drilled hole in the ASSE salt mine. This level was coordinated by ATKINS with twelve Community computer teams participating, among which the ECN played a major role in specifying specifications for the test cases.

The objective of the exercise was mainly to assess the present capabilities of the EC teams with regard to "blind" predictions of rock salt behaviour. Beyond the very satisfactory results obtained by the intercomparison exercise, a first step towards quality assurance of software in this field by a true European rock-mechanics technical community has clearly crystallized through the COSA project.[6]

23.3.1.2. Geoforecasting Studies

The automated generation of predictive scenarios with a view to describing the future geological evolution of specific sites was the subject of the so-called geoforecasting approach, developed by BRGM.

A computer code, CASTOR, allows for the interactive combination of quantified geodynamical factors such as erosion, ground uplift or subsidence, and climatology. The code was partly validated using the case of a real paleo-site, for which the simulated geological evolution could be compared to the actual, over the last 100.000 years.[7] Recent work on CASTOR consists of improving the code's basic geodynamical factors, such as climatology, as well as the software and input/output facilities, e.g. computer graphics.

A similar (but not duplicating) line of action was pursued by Dames and Moore (UK) in the framework of the PACOMA project (see below).

23.3.2. Engineered Barriers and Repository Design

The work in this research item has concentrated on engineering aspects of backfilling and sealing of deep repositories, and modelling of metal overpacks for high-level waste. Design concepts for geological disposal were tested in various projects as discussed below in connection with underground demonstration facilities.

23.3.2.1. Backfilling and Sealing of Radioactive Waste Repositories

The objective of this research item was to develop and test suitable materials and engineering procedures for the adequate placement of the very large quantities of backfilling materials to be used in a full-scale repository. Due to the variety of geological situations depending upon the host rocks considered, the research addressed a large variety of potential techniques which were tested either on the laboratory scale in large mock-ups of galleries or in-situ in underground laboratories.

In the framework of a "Backfilling and Sealing Group," exchanges of expertise could take place between those institutes in charge of disposal operations, and experienced civil engineering firms of the Community.

For granite, the research focussed on tests for the placement and behaviour of various types of materials, such as: improved cementitious mortars to be pumped in vertical and horizontal tubes simulating, respectively, vertical disposal holes for HLW and galleries for ILW (Soletanche, Paris, F); modelling of preplaced aggregate concrete and conventional concrete behaviour for horizontal galleries (Taylor-Woodrow, UK); air-cast improved mortars for ILW disposal (CEA); preformed blocks of compacted clay-based buffer materials for HLW disposal in vertical boreholes to be tested at reduced scale in a heating rig (CEA) then at full scale in the Fanay-Augeres mine (CEA and ENRESA). In parallel, the use of clay-based seals to be placed in boreholes with a view to fracture sealing was tested on scale models, then in-situ (CEA).

As regards clays, the joint in-situ heating experiment BACCHUS in the Mol underground laboratory put together the efforts of CEA and SCK/CEN about the placement of a preformed clay buffer in a 14 m deep borehole. In parallel, the in-gallery disposal and backfilling concept in the Boom clay was investigated as regards near-field induced interactions (SCK/CEN). Finally, the deep borehole disposal concept involving the stacking of waste canisters in large boreholes drilled in clay layers from ground surface will be tested with dummy canisters on the Casaccia site near Rome by ENEA; in this concept, the sealing of the upper part of the disposal holes is one critical issue to be investigated.

For repositories in salt, the most commonly advocated backfilling material is the crushed salt resulting from excavation. Therefore, the work concentrated on the in-situ behaviour of this material used for backfilling of large rooms in the Asse mine, as well as the construction of large plugs or dams which are to isolate sections of repositories (GSF). In parallel, the compaction behaviour of heated, crushed salt used to fill boreholes, 24 cm diameter and about 6 m long, drilled in a salt layer of the "Amelie" French potash mine, was measured in-situ and modelled (ANDRA).

A companion section of this research put together some generic work, such as the historical examination of old and ancient concretes with a view to assessing the durability of this material (Taylor-Woodrow). Quality assurance procedures for an adequate backfilling of repositories on an industrial scale were established (BULLEN). Complex sealing systems involving swelling products such as bentonite or magnesium oxide, and waterproof materials such as bitumen, were being designed (BULLEN) in order to complement the more conventional concepts described above.

23.3.2.2. HLW Container Development

For the assessment of the mechanical performance of containers and/or metallic overpacks for geological disposal of HLW, a coordinated project, COMPAS, included structural code benchmark exercises and mechanical tests on model-scale containers with a view to code validation. Complex loading cases and material behaviour such as buckling, creep failure and fracture propagation were envisaged under relevant repository conditions. Thick-walled stressed shell (mild steel), as well as thin-walled supported shell (titanium) container concepts were considered. The project was coordinated by OVE ARUP with the participation of SCK/CEN, CEA, STEAG Kernenergie, ENRESA and NAGRA (CH). It was again shown that adequate modelling capabilities do exist in the Community on this topic[9].

23.3.3. Migration of Radionuclides in the Geosphere

The bulk of the research in this field was the subject of a second phase of the coordinated MIRAGE project, already initiated in 1983.[10] In order to supply relevant data and models to be used for safety assessments of geological disposal, work was concentrated in four major research areas: geochemistry of actinide and fission products, in-situ migration experiments, natural analogues, development of adequate concepts and calculation tools. Specific reference sites (e.g. Mol, Gorleben, Fanay-Augeres, Drigg, El Berrocal) were identified; the main thrust of the project was on in-situ investigations and on the benchmarking of measurement techniques, concepts and computer codes. The research areas themselves consisted of interconnected, coordinated subprojects in which CEC cost-sharing contract partners, the JRC-Ispra and institutes from Third Countries (Canada, Switzerland, Sweden. etc.) participated.[11,12,13]

23.3.3.1. Geochemistry of Actinides and Fission Products in Aquifers

The essential influence of colloids and of various organic substances, mainly humic and fulvic acids contained in deep or shallow aquifers on the mobility of radionuclides in the geosphere cannot be ignored if a proper modelling of nuclide migration is to be done. Considering the very wide scope of this subject, the work has been focused on three main themes: radionuclide complexation with organic ligands, generation of radioactive colloids in aquifers, and mobility of radioactive complexes and colloids in the geosphere.

In order to study these issues, the Commission has initiated the COCO Club (Colloids and Complexes) which put together the efforts of 21 laboratories, among which the Technical University Munich (FRG) played a major coordination role. In addition to the research carried out in each laboratory, two benchmark exercises were launched. The first one is an action in the field of complexation of radionuclides with humic acids present in some reference sites (Drigg, Mol, El Berrocal, Gorleben, Fanay-Augeres, Ispra). The second exercise concerned the identification and role of natural colloids present in groundwater; the Markham Clinton (UK) and Grimsel (CH) sites were considered for this purpose. Finally, literature surveys on the role of organic matter on the possible mobility of radionuclides in groundwater were performed (RISØ).[14] This pooling of expertise from various laboratories has clearly resulted in a substantial improvement of knowledge about these sensitive questions.

23.3.3.2. In-situ Migration Experiments

In-situ migration experiments were performed on reference sites in order to supply the necessary input data for predictive migration modelling.

The "scale effect" experiment in the Fanay-Augeres uranium mine allowed the determination of the influence of the scale of measurements upon parameters such as permeability and dispersion coefficients, via hydrogeological and tracer tests carried out in this fractured rock mass, under the leadership of CEA.[15]

For the tracer experiments at Drigg, radionuclides were injected in a shallow sand aquifer together with natural and/or man-made organic substances in order to investigate the role of the latter on radionuclide movement. This was an extension of a previous piece of work on the same site, also carried out by BGS. In parallel, the modelling of the experiment was performed by the Delft Geotechnics (NL) jointly with BGS. The underground laboratory in Mol was the site for in-situ migration tests carried out by SCK/CEN in the Boom clay. These include forced advection tests using the radially convergent groundwater flow towards the laboratory, and an associated determination of the large scale in-situ permeability of the clay, of the order of 10^{-12} m/s. Further tests by UKAEA, in cooperation with SCK/CEN, were aimed at studying in-situ diffusion of radionuclides placed in the undisturbed clay, as well as the possibility for high flow rate transport in fractures which might be encountered in clays. Finally, in-situ downhole migration probes to be used in deep boreholes were developed by CEA for hard rock (Foralab probe) and clays (Autolab probe). Supporting data came from the column migration experiments carried out at the JRC-Ispra site.

23.3.3.3. Natural Analogues

It is now commonly recognized that carefully selected examples of naturally occurring geological migration processes, the so-called natural analogues, are one of the most convincing supports for predictive radionuclide migration modelling. Owing to the considerable upsurge of interest in this topic, the Commission took the initiative of establishing in 1985, an international Natural Analogue Working Group (NAWG) whose activities now encompass the items of work described below and carried out at the Community level. This informal alliance of experimentalists and modellers, drawn from research and assessment teams in all the major international programmes, has progressed a considerable way towards clarifying the needs for natural analogues, their realistic potential, and the principles involved in applying them sensibly. In addition to this well conducted scientific work, much attention has paid to the public perception of natural analogues as an efficient support for the conclusion of safety assessments, e.g. PAGIS project (see below). For this purpose, plenary meetings of this group were held in 1985, 1986 and 1988;[16] and a major international symposium was organized in Brussels in 1987.[17]

Natural migration systems in hard rock involved the study of rare earth element transport away from palaeo-hydrothermal zones, such as the one studied by BRGM at Fombillou near Entraygues in France. Transport mechanisms of uranium and thorium from intragranitic ore bodies in French sites (Grury, Auriat) were also considered (CEA). Evidence for matrix diffusion of natural uranium series radionuclides is the subject of a joint research project by the University of Oviedo (E) and the University of Exeter (UK). Finally, an interesting example of an "archaeological" natural analogue was the case of granite blocks immersed in sea water about 30 years ago, in which the diffusion profile of ions such as chlorine was measured (UKAEA).

With regard to sedimentary sequences, work has continued at the Loch Lomond and Needle's Eye sites. The experimental section, carried out by BGS, was supported by the companion modelling work performed at Ecole des Mines de Paris (EMP) and CEA. Other sites, e.g. Broubster, were also studied in the United Kingdom by BGS. Clay-sand sequences in Italy were investigated by ENEA with a view to establishing the role of oxic groundwater in the mobilization of radionuclide analogues (redox fronts, etc.). This was complemented by a demonstration of the large-scale impermeability of clay basins with regard to, e.g. gas and hydrothermal water transport. The interesting example of the Dunarobba fossil forest (Central Italy) showed that fragile materials, like wood cellulose naturally buried under some meters of clay, can survive unaltered for more than one million years (ENEA).[18] Another item of research concerned the diffusion of U-series radionuclides in a sub-seabed sedimentary sequence of the Madeira Abyssal Plain, from which cores were taken during the Marion Dufresne cruise in 1985 (IOS).

23.3.3.4. Calculation Tools

All the above research areas could be considered as the experimental support for MIRAGE, whereas the "calculation tool" approach is aimed at improving the overall modelling capability in the long-term prediction of migration processes. A first set of activities dealt with radionuclide transport computer codes. Advanced tools such as the MICOF code for porous flow (SCK/CEN), the NAM series of codes by UKAEA including NAMMU for porous media and NAPSAC for fractured media, and the specially developed METROPOL code for high density brines (RIVM) were part of this effort to improve modelling capabilities. An attempt at testing the influence of thermal-mechanical phenomena, linked to disposal of HLW in hard fractured rock, on groundwater flow patterns and associated nuclide transport was the subject of a joint effort by ANDRA and CEA using modules of the INCA software. The development of new concepts was not neglected; an example of this is the establishment of a thermodynamic framework to study and quantify the so-called non-dominant transport processes which may operate in some disposal scenarios, e.g. thermal osmosis. This study was carried out by CEA and EMP.

The second basic component of this research area was concerned with the improvement of geochemical codes and data bases. The newly developed WHATIF code series was improved by the inclusion of solid solution capabilities, and the parallel extension of consistent data bases; this latter aspect is envisaged as a first step towards an expert system in this field (RIS). The development and validation of a coupled flow and geochemistry computer model, CHIMERE, is in progress (CEA and EMP); the model was partly validated against flow-through solute transport experiments in porous limestone cores.

In order to ascertain the EC capabilities for geochemical modelling, an international exercise, called CHEMVAL, was promoted within MIRAGE, with joint funding by the UK Department of the Environment and coordination ensured by ATKINS.[19] The objectives were as follows: (a) development of a useable geochemical data base for modelling purposes; (b) verification and validation of geochemical speciation codes; and (c) verification and validation of coupled flow and geochemical codes (Figure 23.3). Fourteen teams and observers from the OECD-NEA Thermochemical Data Base participated in the four stages of this 3-year project, which resulted in a substantial improvement of calculation tools and data for geochemical modelling. This could be considered as a useful step towards quality assurance of the codes. In addition, the validation exercises were carried out against real cases for which data came from the other research areas (COCO, Natural Analogues) of the MIRAGE project. In turn, the validated codes and the CHEMVAL data base could be used to model the MIRAGE natural analogues such as Needle's Eye and Broubster (UK), thus increasing the quantitative role of natural analogues with a view to further model validation.

23.3.4. Shallow Land Burial

A limited effort was devoted to this disposal option in the Third Programme, mainly

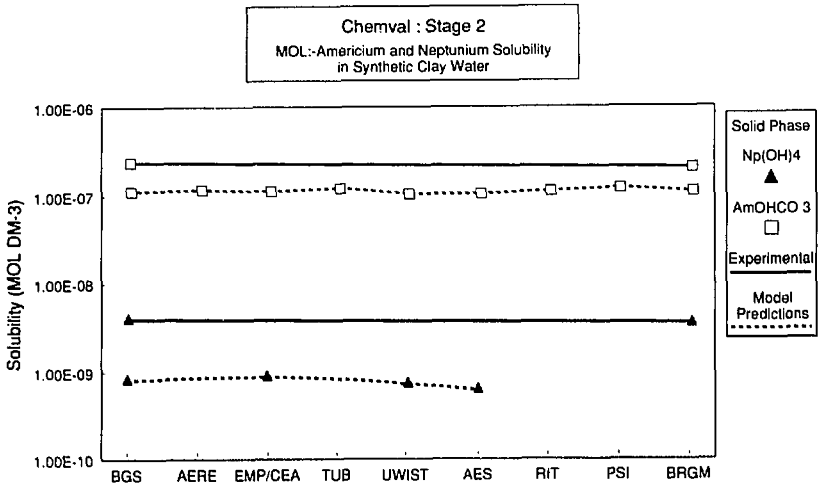


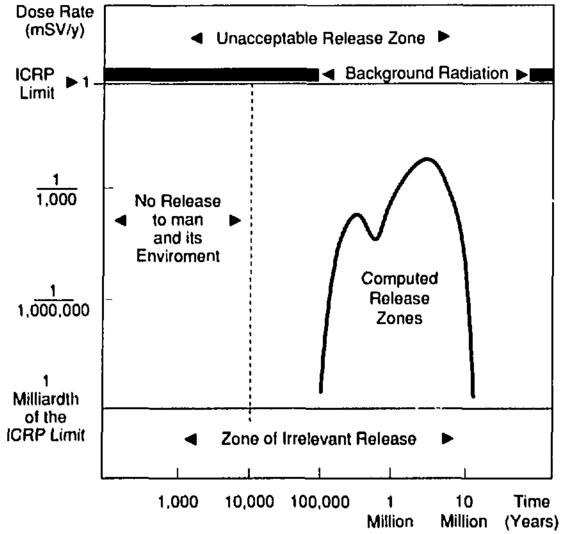
Figure 23.3. CHEMVAL Project. Radionuclide speciation in synthetic groundwater from the Mol site. First comparison between blind calculations (dashed lines) and measurements (solid lines). Names of participating teams are on the horizontal axis.

because of the already existing knowledge and expertise available in some member-states. The work concentrated on the improvement of man-made features of the disposal facilities. A good example was the extensive characterization and optimisation of concrete structures to be used as engineered barriers in shallow burial facilities for low-level waste, e.g. El Cabril (E).

23.4. Safety of Geological Disposal

All the above-mentioned work and the precursors since 1975, have contributed to the Community project PAGIS (Performance Assessment of Geological Isolation Systems) launched by the CEC in 1982. Under the control of a steering committee, a common performance assessment methodology was developed and applied to real sites (which may or may not become disposal sites) in granite, salt, clay and sub-seabed sediments; the main partners were CEA, GSF, SCK/CEN and NRPB respectively. The JRC-Ispra also brought a substantial contribution, mainly by the development and implementation of the LISA probabilistic risk assessment code. Scenarios included "normal evolution," "altered evolution" and "disruptive events;" and due consideration was given to the human intrusion problem. The conclusions have supported the soundness of the geological disposal option in that no radioactivity at all was shown to be released from (hypothetical) HLW repositories for very long time spans, and that the possible doses to man would be, in all cases, extremely low (Figure 23.4).[20] The full results of the recently completed PAGIS project were presented by the CEC to a selected audience during a "PAGIS-Day" in Madrid on June 30, 1989. A similar exercise, concerning medium level and/or alpha bearing waste, was initiated in 1986 (Project PACOMA) and is nearing completion.

This type of studies must also benefit from developments in other fields of science. It is possible that "artificial intelligence" methodologies, such as fuzzy sets theory and belief functions, can be used in order to better cope with uncertainty in models and scenarios for performance assessment. Whether these tools can bring added value, or different view points, compared with probabilistic approaches is still a matter for careful "pilot" investigations led by the CEC.[21]



Pagis-Granite option (reference site, normal evolution)
Evaluated dose rate to man as a function of time
after closure of the waste repository

Figure 23.4. PAGIS Project. An example of calculation concerning the granite disposal option.

23.5. Pilot/Demonstration Underground Facilities

The demonstration facilities mentioned above also contribute to the acceptance of the geological disposal concept, in that they aim at confirming, on site, the design criteria to be taken into account for building industrial repositories, to develop waste emplacement techniques, or to validate sites as being convenient for disposal.

23.5.1. The HAW Project

The HAW project in the Asse salt mine (FRG) concerns the emplacement of thirty high-level radioactive canisters in six boreholes located in two test galleries at the 800 m level in the mine (Figure 23.5). The waste form, which is borosilicate glass spiked with Cs-137 and Sr-90, have been manufactured by Battelle PNL in the USA. They are scheduled to remain in place for a period of five years. For the handling of radioactive canisters and their emplacement, the complete technical system consisting of transportation casks, transport vehicle, disposal machine and borehole slider has been developed and tested. The project is being carried out by the GSF with close co-operation between GSF and the ECN (NL). ECN is in particular responsible for the development of technical components, for monitoring and guaranteeing the retrievability of the canisters, for the procurement of heaters to be installed in two additional boreholes and for the data collection system.[22]

This international co-operation has been enlarged with the participation of ANDRA and ENRESA. The work being performed by ANDRA concentrates on in-situ measurements of gamma radiation doses and on laboratory investigations on radiolytic gas production in salt. The results of laboratory investigations being performed at Saclay (F) will be compared with those of the in-situ measurements in the Asse mine. The activities performed by ENRESA focus on measurements of radiation damage on rock salt. Various salt samples, including samples from Spanish sites, will be irradiated in-situ in the Asse mine and in the irradiation facility of the High Flux Reactor in Petten (NL). The post irradiation analyses will be performed by the Universities of Barcelona (E) and Utrecht (NL).

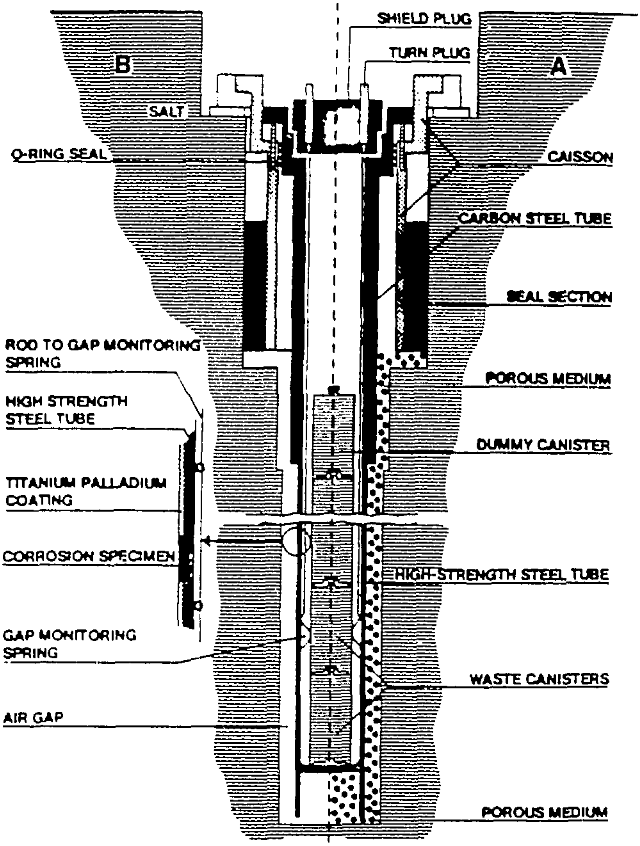


Figure 23.5. The HAW underground demonstration facility (GSF). Cross-section through typical deposition holes drilled in the salt. (Note that all canisters are retrievable.)

It is clear that this action, which is a first of its kind, has grown to a truly international project in which a number of organizations from member-states are participating.

23.5.2. The HADES Project

The HADES project is the second of such facilities and is presently operational in the underground research laboratory excavated by the Studiecentrum voor Kernenergie (SCK/CEN) in the Boom clay layer under its nuclear site at Mol (B). This project is within the framework of the previous R&D programme (1980-1984) and has been operational since 1985, when a test drift was successfully excavated between April and December 1987. The drift is 63 m long and has a 3.5 m inner diameter, and was realized in close co-operation between SCK/CEN and ANDRA. The first section, about 45 m long, was made on behalf of SCK/CEN and is lined with concrete segments; the second section is lined with sliding steel ribs and was constructed for ANDRA (Figure 23.2). This co-operation has been further enlarged by the participation of the Geotechnical Consulting Group (UK).[23]

Building the test drift has been a direct demonstration of mining capabilities in a plastic clay with properties and conditions representative of an argillaceous host formation for disposal of radioactive waste. The two different lining techniques were successfully applied and the results of mine-by-tests showed that the facility and the host rock behave as expected. The test drift will further be used for performing demonstration and validation tests on heat transfer, active source handling (CERBERUS project), gallery heating and backfill emplacement.

23.6. Conclusions and Prospects

In conclusion, the European Community programme and budget on radioactive waste has made, for 15 years, a significant contribution to the development of the concept of deep geological disposal. This has involved the experts, laboratories and facilities of the EC countries and of some non-EC groups linked by bilateral co-operative agreements with the EC.

The third Community conference on radioactive waste management and disposal, which will be held in Luxembourg on September 24-28, 1990, will be an opportunity for the results described above to be presented to a worldwide audience. One message will certainly be that the deep geological disposal concept appears feasible and safe. This concept merits being developed, confirmed and brought to industrial maturity, and it also merits gaining public acceptance.

The next (and fourth) Community programme on radioactive waste, 1990-1994, will contribute to these aims. In particular, efforts will be maintained on experiments and studies to support the evaluation of the safety of disposal, notably natural analogue studies, and on demonstration facilities, whose number is expected to increase.

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Chapter 24

IAEA Radioactive Waste Disposal Programme

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24.1. Abstract

This paper presents the main features and trends of the IAEA programme on geological disposal of radioactive wastes which incorporates projects on research and technical development as well as on regulatory and safety aspects of underground waste disposal. The major tasks of these projects include preparation and updating publications, especially on high-level waste disposal technologies and regulations, development of international standards and criteria, preparation of state-of-the-art documents, promotion of research activities such as studies of migration behaviour of radionuclides in the geosphere, close cooperation with the member states and international organizations and public information on matters related to underground disposal of radioactive wastes. In addition, a number of radioactive waste disposal activities are carried out within other project tasks of the Agency waste management programme including the international waste management data base and technical assistance to member states. The Waste Management Advisory Programme (WAMAP) is the main means by which assistance is being provided to developing countries. A service entitled "Waste Management Assessment and Technical Review Programme" (WATRP) has now been initiated to meet the needs of more advanced countries with nuclear power programmes in providing advice at an international level on the development of their waste management programmes.

24.2. Introduction

The disposal of radioactive waste is an issue of concern and controversy in many countries. Developing countries face problems chiefly with low-level radioactive wastes and the Agency has a substantial programme of assistance in this field. In countries with nuclear power programmes, concern centers on high-level radioactive wastes. It is a common public view in such countries that no adequate solutions have yet been found to these problems and in many of these countries public objections raise obstacles to the selection of sites suitable for the ultimate disposal of high-level radioactive wastes. This public perception is at sharp variance with the view of experts who generally agree that technical solutions already exist which allow the safe and complete isolation of high-level waste deep in geological formations that have been stable over millions of years. The fact that these techniques have not yet been employed on a large scale is probably less due to public objections than to the desirability of keeping the waste at surface level for some years to allow it to lose in heat and radioactivity before it is finally emplaced in the underground disposal sites.

Radioactive waste disposal is a major component of the Agency's Division of Nuclear Fuel Cycle's overall waste management programme. It consists of four projects:

(1) Research and technical aspects of waste disposal,

(2) Regulatory aspects of waste disposal,

(3) Exemption of radiation sources from regulatory control, and

(4) Radiological and environmental effects of waste disposal.

This paper will focus on the first two projects, dealing directly with the subject of underground disposal and related geological problems. Information about the IAEA activities on the two other projects can be found in some recent,[1,2,3] and earlier,[4] Agency's publications.

Underground disposal is for many countries the most realistic and practicable method for the safe isolation of radioactive waste. The Agency's underground disposal programme attempts to address systematically the various problems and areas of interest for the disposal of low- and intermediate-level waste and of high-level and alpha-bearing waste in either near surface repositories, rock cavities, or deep geological formations. The subject areas covered by the programme include:

(1) Generic technical and regulatory aspects such as geoenvironment and safety assessment, safety standards, technical criteria, and basic guidance for specific disposal options;

(2) Investigation and selection of repository sites;

(3) Design and construction of repositories; and

(4) Operation, shutdown and surveillance of repositories.

The IAEA supports the efforts currently being employed in member states towards obtaining a greater understanding and development of given areas by a well-developed mechanism, like providing for information exchange, through coordinated research programmes (CRPs) and scientific meetings, and by producing timely reviews of important topics. The information collected/generated through these activities is available as Proceedings, Safety Series Reports, Technical Reports, Technical Documents, etc. The most up-to-date information on various aspects of radioactive waste disposal is disseminated through the publication of the Agency's INIS Atomindex Abstracts (twice a month) and Waste Management Research Abstracts (WMRA), an annual compilation of programmes, institutions and scientists engaged in radioactive waste management in member states.

From 1978 to 1988, the IAEA programme on geological disposal of radioactive wastes was generally guided by a standing committee, the Technical Review Committee for Underground Disposal (TRCUD), which met annually and greatly contributed to its success. It is gratifying to note that during this last decade, commendable results have been achieved. About 30 reports have been published on basic guidance, regulatory aspects, criteria, safety assessment, research and technical aspects of siting, design, construction and operation of underground repositories. A number of international symposia and seminars on underground disposal of radioactive wastes have been held. Having completed 10 years of service as per its original mandate, the TRCUD was replaced in 1989 by the International Waste Management Advisory Committee (INWAC) with revised membership to give advice to the Agency on all aspects for an integrated radioactive waste management and disposal programme.

24.3. Highlights for 1988

Among the Agency's activities in the promotion of research and development for underground disposal of radioactive wastes, hydrogeological and geochemical aspects are given special emphasis, as it has been recognized that groundwaters are instrumental in the leaching and transport of radionuclides from a repository to the biosphere through the geosphere. The subjects of particular attention include general methodology and techniques for investigations of potential or selected repository sites, including isotope techniques, palaeohydrogeology, research in the near field and for prevention and mitigation of groundwater contamination, development of flow and transport models for specific low-flow, low-permeability environment, which for their validation require large scale in situ experiments, studies of natural analogues, etc.

In 1987, a new CRP "Geochemistry of long-lived transuranic actinides and fission products" was launched by the IAEA for a duration of 5 years. The framework of the CRP, developed at a Consultants' Meeting in Santa Fe, USA, 28-31 March 1988, consists of three main components:

(1) Development of a working hypothesis with focus on laboratory studies;

(2) Testing of the working hypothesis with the focus on the field studies addressing natural production of the radionuclides, the confirmation and the quantification of the processes controlling their migration in various geological systems; and

(3) Transport modelling, encompassing all concepts needed to interpret experimental results.

At present the following countries participate in the CRP: Australia, Canada, China, FRG, Japan, The Netherlands, Poland, Sweden, UK and USA. The first Research Co-ordination Meeting (RCM) was held on 7-11 November 1988 at the British Geological Survey, Keyworth, UK.

In 1988 technical reports on sealing of underground repositories for radioactive wastes and on natural analogues in performance assessments for disposal of the long-lived radioactive wastes and a safety series guidance for regulation of underground repositories for disposal of radioactive wastes were reviewed by the TRCUD, finalized and submitted for publication. The work continued on the preparation of a safety standard document for the underground disposal of high-level radioactive waste after the comments on its draft had been received from member states and on a safety guide dealing with acceptance criteria for the disposal of radioactive wastes in deep geological formations. Both documents are in the final preparation stage.

An IAEA regional training course on handling and disposal of nuclear wastes was convened in the People's Republic of China (Institute of Atomic Energy, Beijing, and Institute of Radiation Protection, Taiwan), 2-27 May 1988. Representatives from the Democratic People's Republic of Korea, India, Indonesia, Malaysia, Pakistan, Singapore and Thailand as well as from the host country participated in the course. Agency efforts are continuing on the promotion of safe radioactive waste management in developing countries in accordance with the Radioactive Waste Management Advisory Programme.[5] A number of the WAMAP missions have focused on waste disposal issues.

New activities included the initiation for development of a safety guide for the siting, design and construction of an underground repository for high-level radioactive wastes, preparation of a source book for providing a better understanding by the public of all waste management activities, and drafting of a waste management information system and data base to include activities within member states covering regulatory aspects, waste management organization and technologies, location and accumulation of wastes and status of repository programmes in various geologic media. Draft reports on evaluation and optimization of post-accident sealing technology for nuclear facilities and on the state-of-the-art review of the underground disposal of radioactive wastes were prepared by consultants.

In addition, in order to collaborate more closely with other international organizations on matters related to geological disposal of radioactive wastes, the Secretariat participated in a number of non-Agency meetings. In particular, scientific contributions were prepared for the International Symposium on Hydrogeology and Safety of Radioactive and Industrial Hazardous Waste Disposal (Orleans, France, 7-10 June 1988)[6] and for the Third Meeting of the CEC Natural Analogue Working Group (Salt Lake City, USA, 15-17 June 1988).[7]

24.4. 1989/1990 Programme Features

Although an international consensus has emerged in recent years that geological disposal is the most appropriate means for permanently isolating radioactive waste from man's environment, a number of problems still remain. The deep geological disposal of high-level waste is a major area of research and development activities for countries with mature nuclear industry, but a number of technical and regulatory problems exist also in relation to the disposal of low- and intermediate-level wastes for almost all member states. Two pressing problems are:

(1) The safety of proposed methods of waste disposal has still to be finally demonstrated and accepted;

(2) The absence of internationally agreed standards and criteria for safe waste disposal is an obstacle to the development and execution of national waste disposal plans.

In 1988 the IAEA waste disposal programme was restructured to better face and provide solutions to these problems. Emphasis is given to an integrated system approach connecting together all concerned technical and regulatory aspects of underground disposal, the environmental consequences of radionuclide releases both on continents and in the sea. The underground waste disposal component of this programme opens its new 10 year phase (1988-97) recommended by the TRCUD. As was mentioned above, it includes projects on research and technical aspects and on regulatory and safety aspects of underground waste disposal both of which are of high priority.

There are both continuity and new features in the 1989/1990 programme in comparison with 1988. Some programme tasks, belonging to the project "Research and Technical Aspects of Waste Disposal" include waste disposal technology and engineering development, and a CRP entitled "Geochemistry of long-lived transuranic actinides and fission products." Other important tasks belonging to this area are the preparation and publication of the following reports:

(1) Safety guide on siting, design and construction of geological repositories for high-level and alpha-bearing radioactive waste. The objective of the document is to give an overview of the current status of repository siting, design and construction activities, and also provide guidance for those who are at the conceptual development stage. The document considers the geotechnical and engineering characteristics of the site and their impact on the design and con-

struction of the repository. In addition, it identifies the level of performance for each barrier of the repository system. It considers siting aspects and how they may affect the quality of design and construction techniques to be used for the shafts, underground workings, transportation of waste materials underground, and the waste package placement.

(2) Safety guide on operation, shutdown and closing of deep geological repositories. Possible topics which might be included in the guide are: receipt of wastes, waste handling and interim storage, waste conditioning for disposal, repackaging/overpacking of wastes, emplacement of wastes, repository openings, surveillance during operational stage, abnormal or accident conditions, occupational health and safety, emergency planning, backfilling of disposal modules, sealing of disposal modules, shutdown conditions and steps, closing of repository, post-operational surveillance, decommissioning of surface facilities and reuse of the site.

(3) Technical report "State-of-the-art review of the underground disposal of radioactive wastes." The objective of the document is to summarize what is known about the techniques and safety of underground disposal of radioactive wastes and what we still need to learn for engineering and construction purposes and to assist in the formulation and development of the Agency's and national programmes. The review is expected also to indicate unresolved areas of scientific interest. Topics to be included in the review are: site selection and site confirmation, overall system approach with possible breakdown into engineered (waste matrix, waste canister, buffer material, etc.) and natural (host rock, surrounding geosphere) barriers, performance assessment for components and barriers, safety assessment of the overall system. Scientific accuracy and factual information are essential for this report including topics in dispute. The review has to indicate how resolution of such disputed topics or compensating of them by greater safety factors in other parts of the multi-barrier system might take place.

The long-term entombment (sealing) of a damaged nuclear reactor, with the objective of ensuring a normal radiation field in the surrounding area and preventing the escape of radioactive materials, came into being after the Chernobyl accident. Activities on post-accident sealing technology are now included in the project, as an entombed reactor, in some respects, represents an unusual type of radioactive waste repository. It is foreseen in the Agency's programme to review the sealing technologies and other technical as well as safety aspects of this radioactive waste isolation system. Its performance and safety are to be assessed with particular emphasis on the near-field interactions among the groundwater, the man-made sealing barrier and the specific radionuclides in the sealed reactor. Optimization of the post-accidental sealing technologies for the radioactive waste isolation system related to the sealing of damaged nuclear facilities are also included.

The importance of the tasks under the project "Regulatory aspects of waste disposal" is self evident. Particularly, when geological disposal is considered, it becomes obvious that it is not only sufficient to develop suitable technologies, but these have to meet the requirements of safety as stipulated in national standards, guidelines and technical criteria. It is recognized that safety of an underground repository depends on a highly complex set of local geological and technical specifications, therefore the formulation of a proper set of quantitative safety standards for construction of a repository is best achieved based on a comprehensive and site specific safety analysis and will always be the responsibility of the competent national authorities. However, though national standards and concordant with them repository designs are and must be site and host rock specific, they nevertheless are all based on a common safety "philosophy" arising from the fundamental concept of multiple barriers - natural and engineered - to assure the containment and isolation of wastes considered necessary. Hence, together with the internationally recognized ICRP, IAEA and OECD/NEA radiological principles and long-term radiation protection objectives, this provides a sound technical feasibility for developing internationally harmonized safety standards on underground waste disposal. The advisability of formulating a set of such standards can be viewed from its objectives:

(1) To provide a basis for those national regulatory authorities which are just starting to develop their standards;

(2) To assist national authorities in member states which have already reached an advanced stage in developing relevant criteria to expedite such development;

(3) To provide guidance to implementing organizations in their work and enable them to assess the acceptability of the disposal system; and

(4) To improve the participation of public and political circles with regard to the acceptability of the waste disposal system.

The need for internationally accepted safety standards and criteria has been expressed in different fora in the past. The Scientific Advisory Committee of the Agency, considering this as an important subject, advised the Secretariat to prepare a Safety Standards report on the subject. The matter was discussed by the TRCUD who opined that initiation of work to prepare a report on the subject would be worthwhile since it could help national authorities to develop their own site-specific standards and criteria. The Advisory Group, which met at the IAEA during the period 12 to 30 September 1988, also recommended that the Agency should continue its efforts and stimulate national bodies to harmonize standards for waste disposal.

To meet this need, the IAEA now intends to publish a series of documents dealing with safety standards and criteria for the underground disposal of radioactive waste. Recently, as mentioned above, work has been done on the finalization of a safety standard document for the underground disposal of high-level radioactive waste and on a safety guide to the standards dealing with acceptance criteria for the disposal of radioactive wastes in deep geological formations. Preparation of other safety standard documents and guides is foreseen by the project on regulatory aspects of waste disposal. At the present time, it is appropriate to publish guidance on standards and safety guides since several countries are about to embark on construction of high-level waste repositories but few have firmly established criteria. The IAEA documents can influence and help them.

24.5. Areas of Concentration for 1991/1992 and Programme Trends

For the IAEA programme in the area of activity under consideration, which has been recently shaped and has just started its new 10-year phase, the major project codes and some areas of concentrations for 1991/1992 may remain basically the same as they are planned for 1989/1990. However, a number of changes will also be necessary to meet recommendations and comments of the above-mentioned Advisory Group and of the first International Waste Management Advisory Committee meeting convened in April 1989.

Recommendations of the INMAC provide strong support to a number of waste management activities, including projects on waste disposal. Of prime importance was the finding that the Committee fully supported the concept of establishing a formal structure for Radioactive Waste Safety Standards (RADWASS) which, in relation to waste disposal, includes the following elements:

(1) Safety fundamentals that are common to the various aspects of waste disposal;

(2) Safety standards, for various specific options of waste disposal; and

(3) Safety guides and practices consistent with the above fundamentals and standards.

The Committee recommends establishing RADWASS to be given the highest priority. In the Committee's opinion, its development will enhance the integration of the detailed activities within the various project codes of the Agency's waste management 1991/92 programme.

24.5.1. Project C.2.01 Research and Technical Aspects of Waste Disposal

INWAC recommended that activities in this project code should be aimed at the generic aspects of waste disposal technology and the associated engineering developments. The present activities associated with high-level waste disposal should continue at the current level. However, more emphasis should be given to disposal concepts for wastes with a hazardous lifetime less than 500 years. No new projects will be undertaken on post-accident entombment before there is an evaluation of the current projects at Chernobyl.

24.5.2. Project C.2.02 Regulatory Aspects of Waste Disposal

A conclusion of INWAC was that activities in this project code should support directly the development of the RADWASS programme. The Committee recommended, in particular, that a project task should be established to develop as safety fundamentals the requirements that are common for different disposal concepts. These fundamentals should provide a basis for the development of a consistent set of safety standards for specific disposal concepts. Another project task should be established to develop a scientific basis for the time-period of concern in safety assessments. The concept of a generic waste classification system (i.e. low-, intermediate-, high-level) for disposal purposes should be reviewed.

The Advisory Group pointed out that the disposal of low-level waste is a well-known problem for which a variety of solutions exist. It is important that the Agency help to clarify this issue, so that the different solutions being adopted can be understood as equivalent from a radiation protection viewpoint. The differences arise from, inter alia, the availability of suitable land, country-specific cost factors and the attitude of public opinion.

This group's further comment was that the management of radiation sources, and in particular the disposal of spent or discarded ones, has represented a serious public health problem in many countries. This problem has to be dealt with in the framework of a comprehensive national radiation protection and waste management programme. The Agency can be very effective in helping developing countries to establish such a programme adapted to their specific needs. To meet these comments, a number of project tasks will be established in 1991/1992 under the Area of Concentration "Strategies and alternatives for low-level radioactive waste disposal" including preparation of recommendations (manuals) for disposal of low-level wastes and sealed sources which will cover regulations, alternatives, options, costs, etc.

24.5.3. Country Specific Assistance

Since its inception, the Agency has assisted its developing member states through training and technical co-operation, by providing assistance in starting and building necessary infrastructures, providing fellowships and financial support through research contracts for carrying out basic research in the nuclear energy field and nuclear applications. Emphasis of the current Waste Management Advisory Programme (WAMAP) is being placed on helping countries to develop a long-term, integrated waste management approach. As demonstrated by the results of WAMAP missions to Hungary and Thailand, the waste disposal issues were the major items of the mission programmes and it is expected that this will continue in the future.

The IAEA has increased its emphasis on country specific assistance not only to developing but also to industrialized countries. In response to requests from member states for peer reviews of their waste management programmes, the Agency is establishing a Waste Management Assessment and Technical Review Programme (WAMAP). On request from member states, the Agency will arrange to assemble teams of international experts to provide critical reviews and assessments on aspects of national waste management programmes. This service provides member states with the facility for having independent international reviews of national plans and projects and may be seen as a way of assisting local specialists in various safety assessment issues and of improving public confidence in national arrangements.

24.5.4. Some Areas of Potential Future International Co-operation

After much public discussion in 1988 of alleged dumping of radioactive waste in Africa, the General Conference called upon the Agency to start work on guidelines for international transfer of such wastes. These guidelines will not be limited to any particular type of waste and countries, but will contain agreed conditions for any international transactions involving radioactive waste. The existence of such guidelines may help not only to prevent irresponsible transfers but also to facilitate transfers which are justifiable and legitimate.

In this light, the idea of international repositories for disposal of radioactive waste may have further development. This concept has been strongly advocated by many of the member states. Past IAEA working groups have considered such approaches as part of regional or international planning for waste disposal facilities,[9] and many countries believe that it is feasible to establish an international waste repository system. However, due to the political nature of such a facility, many international legal, environmental and technical concerns must be addressed prior to further consideration. The discussion during the first INWAC meeting showed that consideration related to international repositories are premature for the IAEA 1991/1992 programme. Nevertheless, the concept remains sound and may be an area of potential future international co-operation beyond 1992.

Another specific area which requires still closer international co-operation in the future is public understanding of radioactive waste management disposal issues. Recently, the Agency has started preparation of a document "Radioactive Waste Management - An IAEA Source Book." The objective of the book is to present scientific, technical, environmental, social and human aspects of the issues involved with radioactive waste disposal and the status of the current scientific and technical solutions and options available to meet the required radiological protection goals. And after completion of the Source Book, the Agency plans to review the role it can play to facilitate the development of national strategies for public understanding and acceptance of waste disposal concepts.

24.6. Acknowledgements

The work presented in this paper involves a number of colleagues from the IAEA Waste Management Section (Messrs. P. De., G. Linsley, D. Squires, K. T. Thomas) and the author owes them his thanks. The careful review of the paper by D. Saire of IAEA is also acknowledged. This paper was presented at the Workshop "Geological Problems in Radioactive Waste Isolation - A Worldwide Review" of the 28th International Geological Congress in Washington, D. C. July 9-19, 1989.

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APPENDIX

Geological Problems in Radioactive Waste Isolation
A World Wide Review

PROGRAM - Saturday, July 15, 1989

Registration	0800-0850
Welcome	0850-0900
Geoscientific Investigations in the Belgian R&D-Programme Concerning the Disposal of Radioactive Waste in Clay, *Arnold Bonne and Pierre Manfroy*	0900-0930
Geological Considerations for Disposal of Nuclear Fuel Waste in Canada, *K. W. Dormuth, W. T. Hancox and S. H. Whitaker*	0930-1000
The French Program for Radioactive Waste Disposal, *F. Chenevier and Y. Marque*	1000-1030
Discussion	1030-1045
Break	1045-1100
Geological Aspects on the Assessment of an Underground Depository for Low- and Intermediate Level Radioactive Wastes in a Former Salt Mine (G.D.R.), *K. B. Jubitz, K. Ebel and K. Putscher*	1100-1130
The Salt Dome of Gorleben: Target Site for the German Repository for Radioactive Waste (F.R.G.), *Michael Langer, Horst Schneider and Klaus Kühn*	1130-1200
Discussion	1200-1230
Lunch	1230-1330
Natural Analogues and Evidences of Long Term Isolation Capacity of Clays Occurring in the Italian Territory, *F. Benvegnu, A. Brondi and C. Polizzano*	1330-1400
Geological Review on Radioactive Waste Isolation in Japan, *K. Hirose*	1400-1430
Research Programme on Geological Disposal of Radioactive Waste in The Netherlands, *H. M. van Montfrans*	1430-1500
Discussion	1500-1515
Break	1515-1530
Radioactive Waste Management in Spain: Main Activities up to the Year 2000, *Carlos del Olmo*	1530-1600
Swedish Programme for Disposal of Radioactive Waste: Site Characterization for High Level Waste *Göran Bäckblom and Per-Eric Ahlström*	1600-1630
Discussion	1630-1700

PROGRAM - Sunday, July 16, 1989

Swiss HLW Programme: Status and Key Issues, *C. McCombie and M. Thury*	0800-0830
Geological Survey for Potential Nuclear Waste Repository Site in Taiwan, *Chao-Ming Tsai, John H. C. Wang, Kuo-Liang Soong and Kuo-Liang Pan*	0830-0900
Geological Aspects of the British Programme for Deep Disposal of Nuclear Wastes, *Neil A. Chapman*	0900-0930
Major Geoscience Issues Concerning Siting the Potential High-Level Radioactive Waste Repository at Yucca Mountain, Nevada *Stephan J. Brocoum, David F. Fenster and Scott G. Van Camp*	0930-1000
Discussion	1000-1015
Break	1015-1030
General Approach and Site Selection Criteria for Low- and Intermediate Level Radioactive Waste Disposal in Yugoslavia, *Antun Saler*	1030-1100
U. S. Nuclear Regulatory Commission's Strategy for Identifying and Reducing Uncertainties Important to Licensing a High-Level Radioactive Waste Repository: Geological Example Applicable to the Yucca Mountain Site, Nevada, *Robert E. Browning, Robert L. Johnson and Philip S. Justus*	1100-1130
An Overview of the Programme of the OECD Nuclear Energy Agency, *J.-P. Olivier, et al.*	1130-1200
Discussion	1200-1230
Lunch	1230-1330
The CEC Action in the Field of Geological Disposal: An Overview, *S. Orlowski and B. Come*	1330-1400
IAEA Radioactive Waste Disposal Programme, *Ivan F. Vovk*	1400-1430
Discussion	1430-1445
Break	1445-1500
Panel Discussion - The Feasibility and Need for an International Repository.	1500-1700