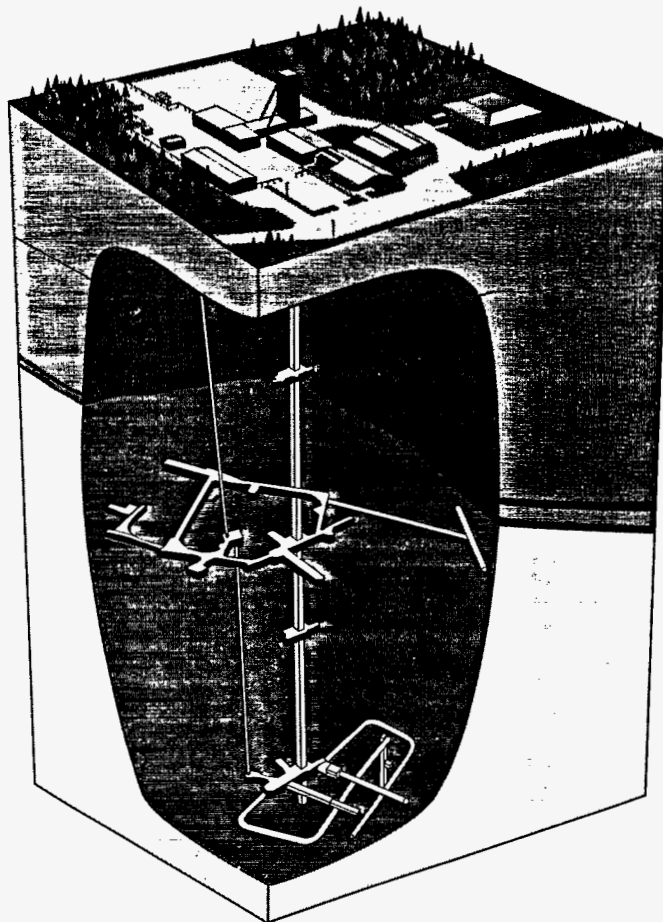


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LBNL-38915
UC-814

Geological Problems in Radioactive Waste Isolation

Second Worldwide Review



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September 1996

Prepared for the U.S. Department
of Energy under contract
DE-AC03-76SF00098

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GEOLOGICAL PROBLEMS IN RADIOACTIVE WASTE ISOLATION

SECOND WORLD WIDE REVIEW

P. A. WITHERSPOON, EDITOR

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ACKNOWLEDGEMENTS

The cover illustration prepared by Atomic Energy of Canada Limited shows a schematic drawing of their Underground Research Laboratory at Pinawa, Manitoba. It is used with permission of Atomic Energy of Canada Limited.

This work was supported, in part, by the Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, through Memorandum Purchase Order EA9013MC5X between TRW Environmental Safety Systems, Inc. and the Ernest Orlando Lawrence Berkeley National Laboratory, under Contract No. DE-AC03-76SF00098. We would also like to thank Dr. J. Russell Dyer for his encouragement and support of this second world-wide review.

The report, "Geoscientific and rock mechanical activities for the radioactive waste repositories in Germany: Key issues, status and future plans," by M. Langer and H. Röthemeyer is reprinted from: Aubertin, M., F. Hassani and H. Mitri (eds.). Tools and techniques in rock mechanics - Proceedings of the 2nd North American Rock Mechanics Symposium, NARMS '96, Montreal, Quebec, 19-21 June 1996, 2050 pp. 2 volumes, Hfl.245/US\$150. Please order from: A.A. Balkema, Old Post Road, Brookfield, Vermont 05036 (telephone: 802-276-3162; telefax: 802-276-3837).

The very careful work of Ms. Jackie Gamble and Ms. Maria Fink on design and production of this report is gratefully acknowledged. We also wish to acknowledge the excellent work of Mr. Flavio Robles on design of the cover and select other graphics of this review.

CHAPTER 1

INTRODUCTION TO SECOND WORLD WIDE REVIEW OF GEOLOGICAL PROBLEMS IN RADIOACTIVE WASTE ISOLATION

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1.1 INTRODUCTION

The first world wide review of the geological problems in radioactive waste isolation was published by Lawrence Berkeley National Laboratory in 1991¹. This review was a compilation of reports that had been submitted to a workshop held in conjunction with the 28th International Geological Congress that took place July 9-19, 1989 in Washington, D.C. Reports from 15 countries were presented at the workshop and four countries provided reports after the workshop, so that material from 19 different countries was included in the first review.

It was apparent from the widespread interest in this first review that the problem of providing a permanent and reliable method of isolating radioactive waste from the biosphere is a topic of great concern among the more advanced, as well as the developing, nations of the world. This is especially the case in connection with high-level waste (HLW) after its removal from nuclear power plants. The general consensus is that an adequate isolation can be accomplished by selecting an appropriate geologic setting and carefully designing the underground system with its engineered barriers.

There is the additional problem of isolating low- and intermediate level waste (LILW). Significant quantities of LILW are generated from various sources, and while they are not as long lived and do not pose the same level of difficulty as HLW, they constitute another, but important, problem for the nuclear industry.

Much new technology is being developed to solve the problems of waste isolation, and there is a continuing need to publish the results of new developments for the benefit of the international nuclear community. Thus, it was decided that after a five-year interval, it would be desirable to gather material on the latest developments

and publish another review on the geological problems of radioactive waste isolation. As shown in Table 1.1, this second review contains reports from 26 countries.

1.2 SOME HIGHLIGHTS FROM THE SECOND REVIEW

1.2.1 Characterizing the Repository Site

Although no repository for HLW has yet been put in operation, significant progress has been made on this subject since the publication of the first review. To decide where to locate a repository for HLW requires a lengthy and detailed process of characterizing the rock mass in which the waste will be placed. Some countries have been working on this process for over ten years, and the wide variety of technologies that are described in this review reflects the fact that, in general, each country has its own internal constraints to satisfy. The process of site characterization can be significantly different depending on the particular type of rock that has been selected as a potential repository site.

The problem of locating a repository for LILW is not as difficult as for HLW, primarily because there is no heat release from the waste to cause temperature problems. Furthermore, a number of the reports in this review describe some well thought out procedures that have been developed to handle LILW. For example, in Slovenia², the siting process has been divided into four steps. In the first step, unsuited areas are omitted from consideration on the basis of certain exclusionary criteria. In the second step, the remaining acceptable areas are further reduced to potential sites according to land use, water resources, seismic and geological criteria. In the third step, several of the most suitable of the potential sites are chosen by comparing their locations on the basis of population, economic feasibility, transport, ecology, and public acceptance. In the final fourth step, a comprehensive analysis of the most suitable sites from

the third stage is made by applying the criteria of the previous steps and an additional factor involving the corrosive nature of the soils, and then a detailed field investigation is carried out to confirm site suitability.

1.2.2 Maximum Repository Temperature

The problem of characterizing the potential repository site for HLW is complicated because of the heat generated by the decay process. If the HLW is not stored at the surface for a lengthy period so as to lose most of its thermal generating capacity, the heat released in the underground can raise repository temperatures well above ambient for thousands of years. In the immediate vicinity of the drift in which the canisters containing the waste have been placed, the temperature of the rock walls may reach as much as 200° C. This depends on the canister spacing and the thermal generating capacity of the waste. When one considers that the area of the repository may be several square kilometers in size, the mass of rock that will be thermally perturbed is significant, and as a result, the problems of understanding the factors that control the coupled behavior (thermal, hydraulic, chemical, mechanical) of such a rock mass are formidable.

As a result, it will be noted in this review that most countries have been following the lead of the early workers in Europe, who have adopted the practice of storing the spent, as well as reprocessed, fuel in surface cooling ponds for 40 to 50 years. This will dissipate the

great bulk of the heat load, so that after emplacement in the repository, maximum rock temperatures will not exceed 100° C. This procedure has been adopted by practically all countries except United States where the cooling period may be no more than 10 years. Currently, the United States is investigating a potential site at Yucca Mountain in the State of Nevada where the rock is a fractured tuff. If a repository is eventually built at this site, the current conceptual repository design would produce maximum emplacement drift wall temperatures of approximately 155° C at about 40 to 60 years after emplacement.³

1.2.3 Rock Types Under Consideration

Another point of interest is the variety of rock types that are under consideration in the different countries where a repository may be built. In the first review, which was mainly concerned with HLW, granitic rocks were the primary rock type under consideration, but it is evident in Table 1.1 that a much wider range of rock types is now being evaluated. In those countries where detailed investigations have been carried out since the first review, excellent summaries are presented of the new technologies that have been developed for several different rock types.

1.2.4 International Waste Management Systems

The establishment of international waste management

Table 1.1. List of countries and rock types being investigated where radioactive waste repositories may be located.

Country	Rock Type for HLW	Rock Type for LILW	Country	Rock Type for HLW	Rock Type for LILW
Belarus	clay, salt	clay, salt	Japan	(1)	
Belgium	clay	clay	Korea		andesite
Bulgaria	granitic, marls		Netherlands	salt	
Canada	granitic		Poland	(1)	(1)
China	granitic		Slovakia	(1)	(1)
Croatia		(1)	Slovenia	marl	
Czech	granitic		Spain	(1)	(2)
Finland	granitic		Sweden	granitic	
France	(1)	(2)	Switzerland	clay, granitic	marl
Germany	salt	iron ore, salt	Taiwan		(1)
Hungary	claystone		Ukraine	granitic, salt	
India	granitic		United Kingdom	volcanics	
Indonesia	basalt		United States	tuff	

Note: (1) Not yet determined; (2) Surface facility.

systems has been suggested in the past and a number of studies has been undertaken^{4,5,6,7} to address the inherent difficulties associated with the disposal of limited amounts of HLW exclusively within national borders. Such a system would be set up to accept and manage radioactive waste from countries with small nuclear energy programs and relatively small volumes of HLW. Bredell and Fuchs⁸ and Lin⁹ have recently discussed the feasibility of such systems, from technical, economical, institutional and ethical viewpoints.

The feasibility of an international waste management system is not discussed in detail in any report of this second review, but as one reads of the activities in the smaller countries (e.g., Switzerland¹⁰, Taiwan¹¹, Ukraine¹²) it is clear that each one is becoming aware of a difficult situation in developing a viable program to handle the problems of isolating HLW. A somewhat different aspect of the need for an international facility may develop in Indonesia¹³ because this archipelago is one of the regions of the world with active volcanism.

The need to consider international waste management systems has been discussed in a recent editorial by Issler¹⁴, who raises some important arguments. From the economic standpoint, countries with relatively small nuclear energy programs and relatively small volumes of HLW are faced with solutions that are essentially uneconomic. A large proportion of the disposal costs is independent of waste volume, particularly those related to concept development, site selection and characterization and, to a large extent, construction and operation of the facility. The costs of site characterization can be very large. For example, the cost of the total effort to characterize the HLW site at Yucca Mountain in the United States is currently about \$2.5 billion¹⁵. This is atypical of costs in Europe, but it serves as an upper bound to illustrate the magnitude of costs associated with this complex problem.

From the practical standpoint, it may be very difficult for small countries to find a HLW repository site that is satisfactory geologically and, at the same time, can satisfy planning restrictions. On the other hand, the geological situation in a particular country may not be favorable, and the country has no choice except to store the waste for an indefinite period. In this respect, regional repositories could provide a safer solution. And from the technical standpoint, the more advanced countries can help others that are disadvantaged by lack of infrastructure, restricted financial means, insufficient technical capacity, or lack of relevant know-how.

Issler has a very good point that puts the situation in context. The United States is planning only one or two repositories for its HLW. Europe, which is comparable in geographic area, has 18 of the 26 countries on Table 1.1, that need disposal facilities. Should 18 national repositories for HLW be constructed, or do not the economic and geologic considerations indicate that two or three regional facilities would suffice? It is understandable that acceptance of international solutions, particularly in the host countries, will be difficult to achieve, but the option of international waste management systems should be kept open and needs careful consideration.

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CHAPTER 2

DISPOSAL OF RADIOACTIVE WASTE IN BELARUS AND COMPLICATIONS FROM THE CHERNOBYL DISASTER

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2.1 INTRODUCTION

A very large area of the Republic of Belarus was exposed to radioactive contamination as a result of the accident at the Chernobyl nuclear power plant on April 26, 1986. Following the accident, the reactor which contained 190.2 t of nuclear fuel, released 1.85×10^{18} Bq of radiation into the environment, of which approximately 70% fell within the territory of Belarus. The released composition included a large amount of radionuclides of iodine, cesium, cerium, barium, strontium, plutonium, etc.

As shown in Figure 2.1, the prevailing winds carried contamination as much as 300 km away from the plant to the north and to the west in Belarus. A total of 46,450

km² (23% of the country) was contaminated, an area that was originally inhabited by 2.1 million people (over 20% of the population). The contamination has affected 1.8 million hectares of agricultural lands, of which 264,000 hectares have been excluded from use. The territory of the Polessie State Radioecological Reserve (131,400 hectares) has been turned into a "plutonium reservation" and is practically excluded from use because of the high levels of contamination.

Although Belarus has no nuclear power plant producing spent fuel, it has some very serious problems in developing appropriate remediation measures to collect and isolate the many kinds of contamination that are spread throughout the affected areas (Fig. 2.1).



Figure 2.1. Areas in the Republic of Belarus contaminated by radionuclides from Chernobyl.

2.2 DECONTAMINATION WASTE AND BURIAL METHODS

The Belarus territory has received a great amount of radionuclide fallout over a significant percentage of its arable land, and although the contaminated industrial and other objects are numerous and widespread, the activity of the decontamination products (DP) is rather low, of the order of 10^{-6} to 10^{-8} Ci/kg. In view of the specific character of the releases from Chernobyl and considering the DP and its associated materials as one category of radioactive waste, the National Committee for Radioactivity Protection (NCRP) of Belarus has adopted the levels of specific activity as shown in Table 2.1.

Table 2.1. Specific activities of radionuclides.

Radionuclide	Specific Activity Bq/kg
Cesium-137	8.5×10^3
Strontium-90	3.7×10^4
Other beta-emitters	7.4×10^4
Plutonium and other transuranic elements	3.7×10^2

An effective program of decontamination outside the 30-km zone (plutonium contamination zone around Chernobyl) was carried out in the period 1986-1988. As a result, 12 million m² of exterior surfaces of buildings and other constructions were cleaned, 13.3 million m³ of contaminated ground were removed and buried, and 7570 old buildings were demolished and buried. These DP were stored far from populated areas, mainly in unprepared sites (such as flat areas, gullies, sinks, old quarries, etc.). About 980,000 m³ of DP and other contaminated refuse are located in 69 partially equipped repositories and five makeshift burial grounds. All these sites are constructed in zones where the ¹³⁷Cs activity of the soils is 15 Ci/km² and above; the gamma radiation exposure dose rates in the storage sites vary from 0.03 to 0.23 mR/h. The cumulative activities total 1.9 TBq for ¹³⁷Cs, 0.14 TBq for ⁹⁰Sr, and 2.6 TBq for ^{239,240}Pu.

Most of these burials are ecologically unsuitable, and the radioactive wastes placed there need to be reburied. A concept and strategy for reburial have been developed, and sites with a suitable geology and geomorphology for constructing repositories have been selected. When selecting sites for DP repositories, the fol-

lowing factors have been considered:

- Location of testing grounds in evacuation zones and obligatory evacuation of people from areas where the activity exceeds 40 Ci/km²;
- Correspondence of the geologic and hydrogeologic conditions of the locality to the requirements for safe radioactive waste isolation;
- Hydrogeologic conditions of the territory with reference to flooding and seasonal water levels, areas subjected to flooding, etc.;
- Structure of atmospheric circulation and seasonal wind patterns in relatively uncontaminated areas and populated areas; and
- DP transportation routes, quality of major and secondary highway routes (near cities), dust generation during loading, transportation, etc.

A model to forecast the migration of radionuclides away from waste repositories has been developed for recommended objects with given migration parameters.

2.3 PROGRAMME FOR DEEP DISPOSAL OF RADIOACTIVE WASTE

In the context of the government programme to construct nuclear power plants in the future, sites for their location have been selected, and a preliminary investigation of geological conditions has been carried out to locate potential sites for repositories for high- and medium-level radioactive wastes. Three rock types have been recognized as potentially being able to provide satisfactory conditions for radioactive waste disposal: (a) the crystalline basement, (b) salt beds, and (c) thick deposits of monomineral clays.

As shown on Figure 2.2, the territory of Belarus has been subdivided into zones showing various conditions to be considered in selecting sites:

- Areas marked Zone I are where the depth to basement ranges from 0.0 to 0.4 km and where conditions are considered very promising for engineering and constructing repositories in basement crystalline rocks;
- Areas marked Zone II are where the depth to basement ranges from 0.4 to 0.6 km and where conditions do not show much promise for repositories in basement crystalline rocks;
- Areas marked Zone III are where the depth to basement ranges from 0.6 to 1.5 km and where conditions

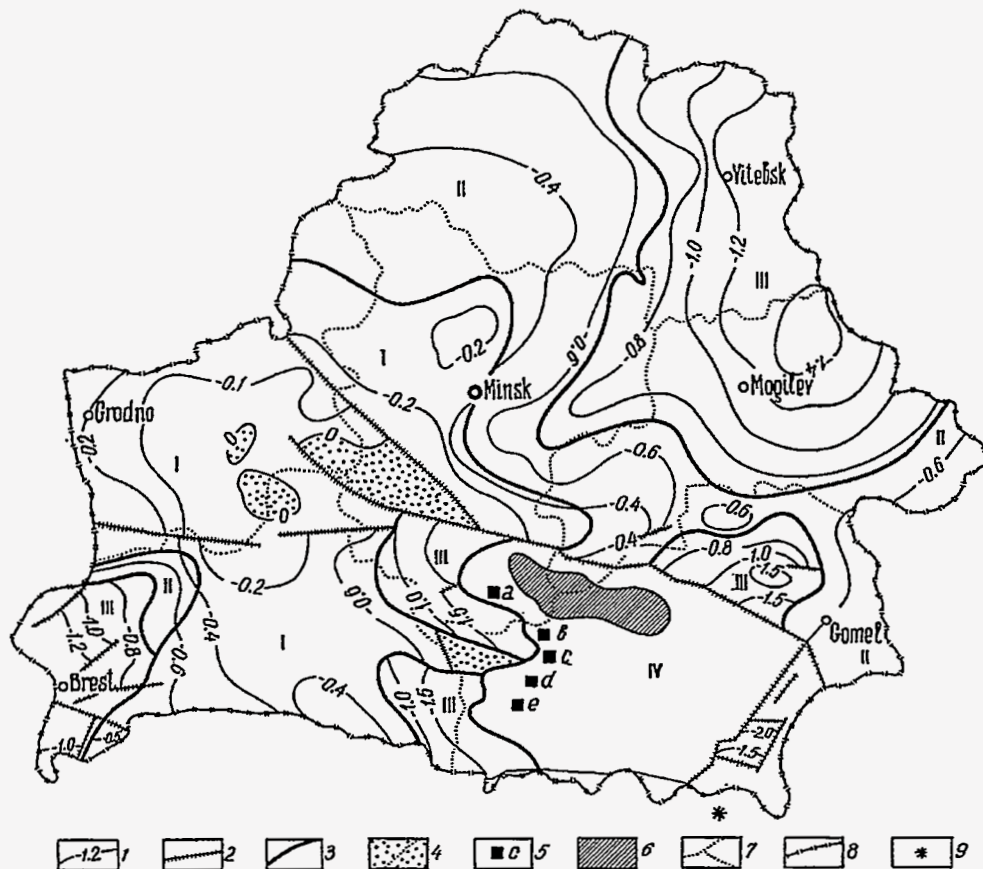


Figure 2.2. Geological division of Belarus into zones in accordance with conditions for medium- and high-level radioactive waste isolation. Legend: 1 - isolines showing depth to crystalline basement (km); 2 - tectonic faults penetrating through the sedimentary cover; 3 - boundaries of zones with different conditions and potential for waste isolation. Symbols for regions with geologic structures considered as primary candidates for repositories: 4 - crystalline basement of Bobovnya, Slonin and Mikashevichy uplifts; 5 - salt diapir domes of: a - Novaya Dubrova, b - Zarechie, c - Kopatkevichy, d - Konkovichy, e - Shestovichy; and 6 - palygorskite clay beds of Pripyat Graben. Other symbols: 7 - boundaries of districts; 8 - frontier of Belarus; and 9 - Chernobyl nuclear power plant.

show very little promise for radioactive waste repositories; and

- The area marked Zone IV is the Pripyat Graben that is considered to have highly promising geological structures for waste repositories in: (a) stratified saliferous formations of Middle and Upper Devonian, (b) domed salt diapirs of the Upper Salt strata, as well as in (c) palygorskite clay beds of Upper Devonian strata.

Crystalline rocks are exposed or overlain by Anthropogene deposits of limited thickness within the Central-Belarusian massif, Ukrainian shield and Mikashevichy uplift (horst). The Central-Belarusian

massif with the Bobovnya uplift of granitic rocks (100-170 m in thickness) and the Slonim uplift of granulitic complexes with blastomylonite show the greatest promise for a site for radioactive waste isolation.

Salt formations cover a vast area (23,000 km²) within the Pripyat Graben and are represented by two Upper-Devonian salt strata: (a) Upper Frasian (up to 1100 m thick), and (b) Upper Famennian (up to 3000 m thick zones of diapirism) separated by terrigenous-carbonate strata. Salt formations occur in zones of diapirism in a depth range of 300 to 400 m and have the potential as sites for waste disposal (Novaya Dubrova, Zarechie and Kopatkevich uplifts on the northwest, and Konkovichy

and Shestovichy uplifts, on the southwest side of the graben).

Large deposits of palygorskite clays are found in the Pripyat Graben at depths of 80 to 120 m, and with thicknesses of as much as 140 to 150 m, they are of particular interest as potential sites for radioactive waste repos-

itories.

Acknowledgments

These investigations were sponsored by the State Committee of the Republic of Belarus on the problems of the Chernobyl consequences.

CHAPTER 3

GEOLOGICAL RADWASTE DISPOSAL IN BELGIUM RESEARCH PROGRAMME, REVIEW AND OBJECTIVES

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Executive Summary. In the early seventies, SCK-CEN launched a research programme on the geological disposal of long-lived radioactive waste. Investigations were concentrated on argillaceous formations because of their abundance at various depths in some parts of Belgium, their expected favourable properties and the virtual absence of salt and/or unfractured hard rock formations in the country. Among the argillaceous formations, the Tertiary "Boom clay" layer was tentatively selected for site characterization studies. In this first phase, the Research and Development programme consisted of laboratory studies on clay core samples and observations on the geology and hydrology of the area. The initial results were very promising with regard to sorption properties of the potential host rock, its chemical stability, permeability, etc.

Early in the programme (1980), an underground laboratory (HADES) was constructed in the clay at the Mol site; a tunnel, 35 m long and 3.5 m in diameter provides a large number of access possibilities to the clay formation, at a depth of 223 m. The first objectives were related to the technical feasibility of gallery excavations in plastic clay under high lithostatic pressures and to the evaluation of the compatibility of vitrified HLW and candidate container materials with the clay, in close to real conditions. In 1988, an additional 60 m long drift was built for integrated tests, e.g. the impact of temperature and radiation. In the meantime, much experience has been gained on sampling of fluids and solids, in the characterization of clay and waste forms; an important scientific data base is now available at SCK-CEN, specifically for vitrified waste and "Boom clay."

This formation - and site specific approach - allowed SCK-CEN to collect, in a short period of time, valuable results and input data for required modelling work.

Some preliminary observations could be made:

- using conventional civil engineering technology, it is technically feasible to drive horizontal galleries in plastic clay, at a depth of more than 200 m, with an internal diameter of at least 3.5m, without special ground conditioning, such as freezing;
- using available experimental data about permeability and retention properties of the host rock (Boom clay), preliminary safety assessments were carried out for many scenarios from natural evolution to important disruption. For the reference mix of reprocessing waste (HLW, MLW, hulls) from a 40 y nuclear programme in Belgium, the highest calculated dose to population, for a normal evolution scenario and water well pathway, is of the order of 3×10^{-7} Sv/a, which can be compared with a dose constraint of 10^{-4} Sv/a, in use in several countries; these doses would occur after a period of about 60,000 years.
- stabilizing factors in the Boom clay are its cationic exchange capacity, the strong reducing conditions due to finely dispersed pyrite and humic materials intimately associated with the clay minerals and a slightly alkaline environment caused by the occurrence of carbonates; and
- the methodology for risk assessment was established and tested in the framework of an international benchmark exercise in cooperation with the European Commission and the Nuclear Energy Agency of the OECD.

Observations and earlier assessments also illustrate remaining areas of uncertainty which require complementary R&D or new studies and demonstrations. Furthermore, the validity of present evaluations and preliminary conclusions, mainly in view of the very long term safety, will benefit from an iterated validation of

models and even comparisons with studies on natural analogues.

3.1 INTRODUCTION

In the present context, the R&D programme of SCK-CEN on radioactive waste management is focused on the characterization of conditioned waste and its underground disposal in geological formations.

Although in the past (1960 to ~1985), SCK-CEN has run several projects on waste treatment and conditioning (mainly low-level and alpha-bearing waste), very little is still being pursued in this area, given the commercial availability of industrial processes and the fact that the waste treatment and conditioning has been entrusted to a separate company, BELGOPROCESS. However, this trend may have to be adjusted some time in the future for reasons of optimization and the development of new waste types resulting from e.g. decommissioning and/or site restoration programmes.

With regard to characterization of conditioned waste, the programme aims at quality control (verification of compliance with contractual quality criteria), characterization of the "source term," which includes studies of corrosion phenomena and compatibility of the conditioned waste form, and its package with the intended geological environment. Attention also has to be paid to "acceptance criteria" since the total radiological capacity of the repository is obviously limited, and non-radiological factors (e.g. temperature and residual thermal capacity of the waste and potentially interfering components) may enhance the mobility of radionuclides in the repository formation. Furthermore, the occurrence of chemo-toxic components in conditioned waste or packages deserves a minimum of attention.

With regard to geological disposal, the R&D programme, initiated by SCK-CEN, deals mainly with the disposal of vitrified high-level waste from reprocessing and other alpha-bearing wastes. Other types of waste are to be considered in the future such as, for example, non reprocessed spent fuel or spent MOX fuel since it is clear that, even if reprocessing remains the reference scenario, at least some spent fuel is not suited for industrial reprocessing.

The R&D programme on disposal proceeds stepwise and cautiously since options have to remain flexible until adequate scientific and technical ground is available to support decisions.

In the exploration of geological formations (1974) for the implantation of a repository in Belgium and after consultation with the National Geological Survey, preference was expressed for a deep clay formation (called "Boom clay") at and around the site of Mol. This early preference, resulted from a number of facts, e.g. the absence in Belgium of any salt formations, the highly fractured nature of most hard rock formations, the natural retention capacity of clay, and the fact that major nuclear facilities were already installed in the Mol area. Consequently, R&D and assessment studies became mostly site-specific or at least formation-specific, without anticipating the conclusions of a more detailed site selection procedure.

The Boom clay belongs to the Rupelian formation and is underlain by the Berg sands (Rupelian aquifer) and overlain by the Neogene aquifer. These two water bearing formations are not considered as barriers, although they could have good sorption properties for the radionuclides. Rather early in the programme (1980), an underground laboratory was constructed in the clay at the Mol site at a depth of 223 m. The underground laboratory was intended to evaluate the technical feasibility of such a construction and to become an *in-situ* facility for performing tests in close to real conditions within the High Activity Disposal Experimental Site (HADES) project.

The current R&D programme is focused on site characterization (mechanical, physicochemical, and hydrogeologic properties) and performance assessments. Understanding the basic phenomena which control the retention and/or mobility of radionuclides in the clay received high priority. A first interim safety report (SAFIR) was produced for the Authorities in 1989. The main conclusion was the absence of counter-indications against the principle of disposal in clay. The next preliminary safety report is to be submitted around 1998 and is meant to be an important milestone in the selection, or decision making, process.

For the near future, investigations on basic phenomena of physical chemistry and geohydrology are to be continued; in addition, a number of areas may require much more study and investigation such as:

- impact of radiation and heat on retention/mobility of radionuclides in clay; these near-field effects may affect important factors such as the length of cooling time in surface storage facilities prior to transfer into the repository and/or the conceptual design of the

- repository;
- influence or significance of non-radioactive components in the anaerobic environment of the repository (e.g decomposition products of organic materials). In case of adverse effects, they might lead to the consideration of alternative conditioning processes, depending on the acceptance criteria for packaged waste; and
- other issues are to be considered as well, e.g position with regard to retrievability, reduction of uncertainties with regard to some major characteristics and to the time scales applicable to geological disposal.

The above programme items require a major extension of the present underground facility to perform larger scale integrated *in-situ* demonstration tests. This important decision has been recently taken and after 1998 will lead to doubling the present capacity.

3.2 THE HADES PROGRAMME AT SCK-CEN

The R&D programme on geological disposal was initiated in 1974 by SCK-CEN and received scientific and financial support from the European Commission from the very beginning. Since 1985, it has been heavily supported by the National Radioactive Waste Agency (ONDRAF/NIRAS), which is in charge of the implementation of the disposal programme.

With a total installed nuclear power of 5.5 GWe and a 40-year operational period for the Belgian nuclear power plants, the volume of waste to be produced of low, medium and high activity can be estimated to be 150,000 m³, 39,000 m³ and 4000 m³, respectively. These volumes do not yet include the decommissioning waste.

The first category of waste contains small quantities of short- or medium-lived radionuclides (half-life not exceeding thirty years); the current option is to dispose this waste at the surface; shallow land burial is considered in Belgium as the reference solution but will not be examined in the present document. Earlier disposal studies resulted in a report submitted by the waste management authority (NIRAS/ONDRAF) in 1993 to a national advisory scientific commission; they are being updated and extended according to the recommendations of this commission.

Two other types of waste are considered in Belgium for underground disposal:

- alpha-contaminated waste (concrete or bitumen

matrix) containing significant quantities of medium-lived radionuclides (half-life exceeding 30 years); it results from specific fuel cycle operations (spent fuel reprocessing, fuel assembly manufacturing) and does not generate heat; and

- vitrified heat-emitting waste (glass matrix) containing a mixture of short- or medium-lived radionuclides in high concentrations, and long-lived radionuclides which are usually alpha emitters. It generates a significant heat power, owing to the fission products content.

Table 3.1 presents some more details on these waste types and volumes.

Table 3.1. Data on radioactive waste types in Belgium.

Waste Type	Matrix	Volume Total (m ³)
HEAT EMITTING WASTE		
Cogema high-level waste	glass	784
Cogema cladding waste	concrete	2,860
Eurochemic high-level waste	glass	265
	Total	3,909
ALPHA WASTE & OTHER		
Technological alpha waste	cement	8,419
MLW concentrates	concrete	20,430
Reactor operating waste	concrete	2,724
Coprecipitation sludge	bitumen	3,310
Eurochemic MLW concentrates	bitumen	2,765
Mox production waste	concrete	1,353
	Total	39,001

It is assumed in the present reference scenario that the operation of a repository for underground waste disposal could start in 2035 to last until 2070/2080 (closure phase). This requires, for vitrified waste, a temporary surface storage of about 50 years allowing the heat output to be significantly reduced. This limited heat output in the repository is intended to produce temperatures not exceeding 100° C in the host clay at the container/clay interface and is one of the basic assumptions for the definition of the R&D programme and associated processes to be considered.

3.2.1 Historical Review of Hades Program

Early studies on potential host formations for geological disposal have indicated that, in Belgium, clay and shale

layers can be taken seriously into consideration. One of the potential formations which was identified is the Boom clay at the Mol-Dessel site situated in northeastern Belgium, where the SCK-CEN and other nuclear facilities are located. The following guidelines for the provisional selection (for experimental purposes) of the Boom clay layer were considered: the anticipated future stability of this 30 million year old formation as well as its depth, thickness, relative homogeneity and sorption/retention capacity (Heremans and Baetslé, 1978).

The research programme was started about 20 years ago by SCK-CEN, which concentrated its activities on verification of basic phenomena, safety and technical feasibility. Several partners from Europe and abroad joined the programme during the second decade and, through their own competence, contributed to the integration of different scientific and technological skills and approaches (Bonne and Collard, 1992).

3.2.2 Approach and Major Achievements During First Two Decades of Programme.

Beside the selection of the formation (and experimental site), the first decade (1974-1984) was dedicated to verify whether the characteristics and properties of the Boom clay layer were really promising for hosting a geological repository.

The first drillings were performed on the SCK-CEN site from 1975 onwards; and analyses of core samples were made to determine lithological, chemical, mineralogical, ion exchange and geomechanical properties of Boom clay and, in some cases, of the surrounding strata. Geohydrological studies were undertaken; a preliminary repository design and a probabilistic risk assessment methodology were developed. Simultaneously, a catalogue of all potential formations occurring in the country was established. From these studies, it was concluded that the Boom clay satisfied the expectations; this plastic material has good sorption capacities and provides very low permeability and low but sufficient heat conductance. It is sufficiently thick and homogeneous and it is chemically and mineralogically stable. Preliminary experiments on corrosion/heat transfer were performed in parallel from an open clay pit in Terhaegen, near Antwerp.

The next step was to demonstrate that it was technically feasible to build a repository in such a plastic material and to strengthen our capabilities in the area of safety assessment; in the latter, a collaboration with JRC Ispra

was an important feature (D'Alessandro and Bonne, 1981).

An underground research laboratory (URL) was built according to specifications which were based on very pessimistic hypotheses (afterwards found to be unrealistic) about the plasticity and perviousness of the Boom clay. For example, the freezing technique was not only used in sands to sink the shaft through these water-bearing formations but also in clay to lower the anticipated convergence rate.

The approach became fully site and formation specific; the site of Mol was placed in a larger geohydrological context, extending the regional observation network on a 2,000 km² area around Mol. Both clay and surrounding geologies were intensively investigated from various perspectives (geochemical, geomechanical, hydrological and geophysical). Due to an increasing amount of available information, the Boom clay became progressively a reference case.

For the critical issue of geomechanics in clay, collaboration was started with ANDRA, the French waste management agency; the digging of a small experimental shaft and gallery in non-frozen clay demonstrated the possibility of excavating and tunneling in the plastic Boom clay at such a depth.

During the second decade (1984-1994), the URL became fully operational; several experimental set-ups were installed in clay for studies on corrosion, hydraulics, migration and geomechanics. A new and challenging field of demonstration was opened with the CEC programme on demonstration and pilot facilities. The HADES URL was extended by tunneling a test drift for demonstration purposes as illustrated in Figure 3.1.

This facility, now called URF (Underground Research Facility,) consists of 100 metres of galleries lined with cast-iron, concrete or steel ribs, providing direct access to the clay mass. In particular, the test drift offered the opportunity to perform large scale integrated tests under conditions close to those expected in and around a final repository.

Validation exercises for the modelling of different processes were launched and extensive performance assessment exercises were carried out, as the "Performance Assessment of Geological Isolation Systems" (PAGIS) and the "Performance Assessment of Confinements for Medium-level and Alpha waste,"

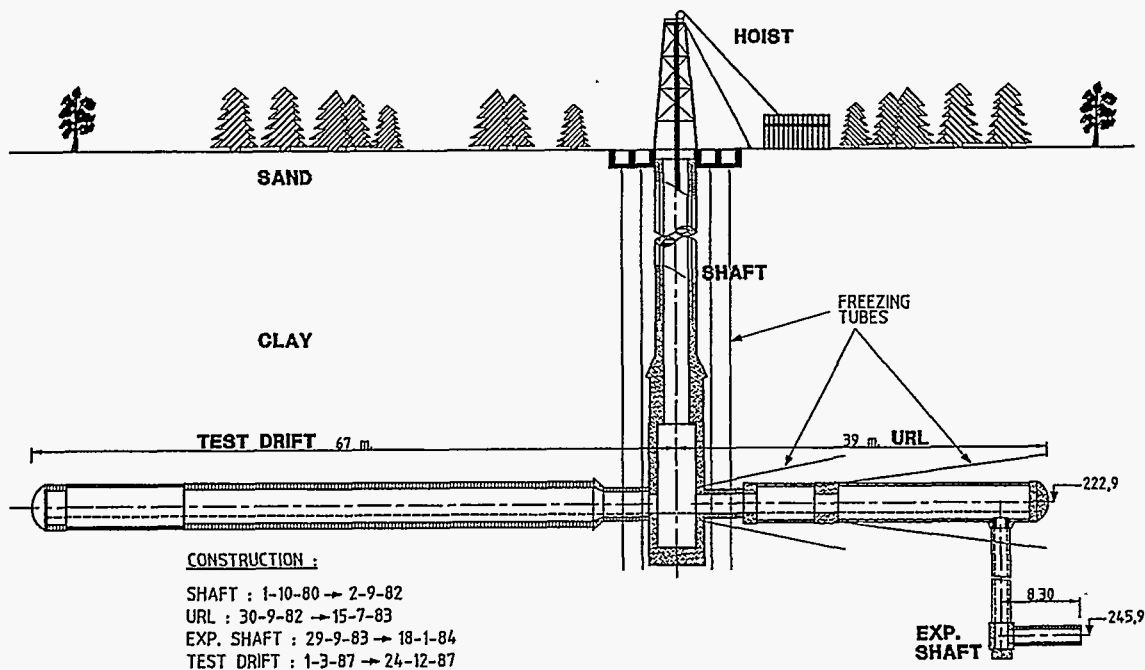


Figure 3.1. The underground research facility (URF) HADES.

(PACOMA) within the framework of the E.C. Both studies were updated, and results were published in the "Updating 1990" (Marivoet, 1992). A methodology was elaborated with the involvement and consensus of a large number of scientists in different member states, active in the various fields of this multidisciplinary activity; the broad contribution from the latter activity had a very positive impact on confidence building.

In 1990, an international commission of experts, formed by the Belgian Secretary of State for Energy, evaluated a Safety Assessment and Feasibility Interim Report (SAFIR) on the geological disposal of waste prepared by NIRAS/ONDRAF (1989); the results of the research carried out by SCK-CEN on final disposal in Boom clay were the main contribution to this report.

These successive actions confirmed the choice of the clay option in Belgium and the continuation of the site characterization programme on the Boom clay layer at the Mol-Dessel site as a potential host formation essentially for long-lived waste. They also define the R&D priorities developed in the current programmes on the different components of the disposal system. As a result of these continuing interactions, tangible progress has been made through improvements in the SCK's characterization programme, e.g. more recently regarding the study of the performance of the engineered barriers in the near-field. Present and future developments are

detailed in the next chapters.

3.3 OBJECTIVES AND BASIC ASSUMPTIONS OF HADES PROGRAMME

3.3.1 Objectives

Safe disposal of radioactive waste is one of the key issues in the environmental concerns of the nuclear industry. In particular, the disposal of long-lived waste, specifically spent fuel and vitrified high-level wastes, is important. Disposal in deep geological formations is at present the most promising option, which requires one to meet the following objectives:

- provide reliable data on characteristics of waste and the geological environment;
- demonstrate the feasibility of disposal concepts e.g. in underground laboratories; and
- assess the safety and acceptability of disposal systems by developing and applying validated methods to the modelling of the various phenomena which control the release and migration of radionuclides from the repository into the biosphere.

3.3.2 Methodology

In order to assess the performance of individual components of the disposal system as well as that of the inte-

grated system, the current R&D programme covers mainly research on basic phenomena, demonstration tests and safety studies.

The geological disposal of long-lived waste is essentially based on a "multi-barrier" concept; several "engineered" barriers (overpack, backfill, gallery lining) are installed between the waste matrix itself (primary containment) and the host rock. The purpose is to delay (e.g. by 500 to 1000 years) the release of activity from the repository structure into the geological environment. The latter time period corresponds approximately to the thermal phase of the repository. Consequently, several coupled effects with temperature can be avoided in the host clay, provided the required performance of these engineered barriers can be guaranteed.

Phenomena relevant to repository performance are generally subdivided into those occurring in the near-field and those occurring in the far-field (geosphere). By near-field, one generally considers the engineered repository structure (including the waste packages and engineered barriers) and those parts of the surrounding rock whose characteristics have been, or could be, altered by the repository or its content (excavation, temperature, radiation).

Any assessment of the performance of geological disposal refers to a conceptual design of the repository and, in particular, to the characteristics of the near field. Information concerning the Belgian reference concept is described in a separate section (see Section 3.3.4).

3.3.3 Performance of Near-Field

An essential distinction for disposal in clay, with regard to disposal in granite, consists of the requirements and objectives of the near-field.

In hard rock, the components of the multi-barrier containment and essentially the backfill material are to be considered as primary barriers which ensure the isolation of the system for the time periods required. In this context, the backfill must preserve alkaline conditions during a very long time period in order to prevent dissolution of key radionuclides and to provide sorption capacity and controlled porosity and permeability. The host geological formation is supposed to provide structural stability, a predictable groundwater flow, and a suitable long pathway and travel time for radionuclides to reach the biosphere.

For argillaceous formations and particularly for the

Boom clay formation, the host "rock" is the primary natural barrier against radionuclide migration; it provides good sorption capacities, very low permeability, and given the composition of the clay, chemically reducing conditions. The backfill has to provide geomechanical and geochemical stability and compatibility.

3.3.4 Repository Concepts in Belgium.

We are considering for geological disposal the long-lived medium level waste (MLW), heat producing vitrified high-level waste (HLW) and spent fuel (SF), but for the latter category, no detailed concept has yet been worked out.

Since 1978, different repository concepts have been considered for high-level and long lived radioactive waste in the Boom clay formation at Mol. The reference concept, now considered by NIRAS/ONDRAF, is illustrated in Figure 3.2. Heat producing high-level and long-lived, medium-level waste would be emplaced in separate disposal galleries. Approximate dimensions (expressed in terms of the inner diameter) for the different components are 6 m for the shafts, 4 m for the primary galleries and 2 m for the HLW disposal galleries. The length of the disposal galleries would be 800 m (4 sections of 200 m). Concrete would be used for lining the shaft and galleries. The lining is designed to ensure mechanical stability during the repository's operational phase.

For the non-heat producing long-lived MLW, the galleries would have an inner diameter of 3.5 m and the section would be filled with MLW canisters, the voids being backfilled, possibly with concrete (see Fig. 3.2).

The design of the HLW disposal galleries is more advanced (see Fig. 3.3) and will, during the next 10 years, be the main subject of the PRACLAY project. The latter requires a substantial extension of the present URF; it is managed by an Economic Interest Group (E.I.G.) where SCK-CEN and NIRAS/ONDRAF are represented. The PRACLAY project is a thermo-mechanical experiment intended to simulate a full scale disposal gallery for heat-emitting waste and to quantify the extent of the disturbance induced in the surrounding clay.

According to this concept, the HLW canisters, simulated by heating elements, are assumed to be placed in long thin metallic tubes in the centre of the disposal galleries. These tubes are designed to remain intact during the thermal transient of the heat producing waste. The thick-

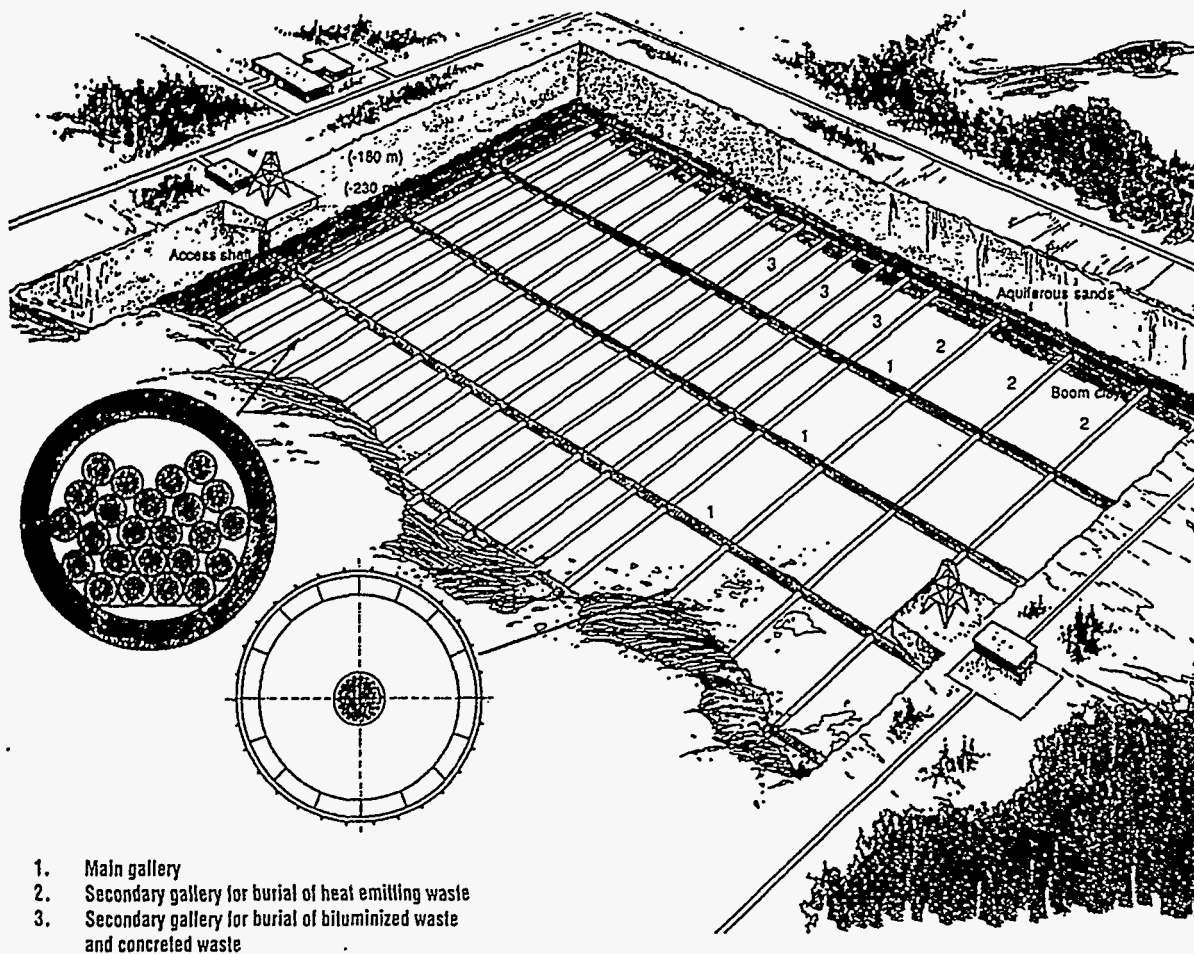


Figure 3.2. Present Belgian reference disposal concept (NIRAS/ONDRAF).

ness of this "overpack" will have to be sufficient to guarantee its role as a reliable barrier during the thermal phase of the disposal, and sufficiently low to limit the potential generation of gas, through corrosion, in the anaerobic phase. The void between the metallic tube and the concrete gallery lining would, according to the present concept of NIRAS/ONDRAF, be backfilled with pre-compacted calcium bentonite blocks.

The option of retrievability or "long term storage" is examined abroad in some disposal programmes (France, the Netherlands, etc.), possibly in connection with later "advanced reprocessing." However, in Belgium, easy retrievability is not considered, up to now, as a requirement in the different disposal concepts. It is assumed that, with the necessary capital and effort, the retrieval of the waste will always be possible during a limited time period, generally considered to be in the range of 50 to 100 years. Only preliminary studies related to the impact of retrievability on performance assessment

might be launched in the near-future by SCK-CEN, providing European partners join the effort.

For the disposal of spent fuel, conceptual studies are in a preliminary stage. The main differences compared to the heat producing HLW are the longer thermal transient to be considered, the content of the total inventory of plutonium and the larger dimensions of the packages. Given the limited dimensions of the clay disposal infrastructure, a size reduction and a form of preconditioning of spent fuel might be required.

3.4 PROGRESS OF CURRENT RESEARCH AND STUDIES

An understanding of the migration processes in the host rock, together with the hydrogeological context of the host and surrounding formations are of prime importance for the long term safety of a reference geological disposal concept. Furthermore, one has to take into

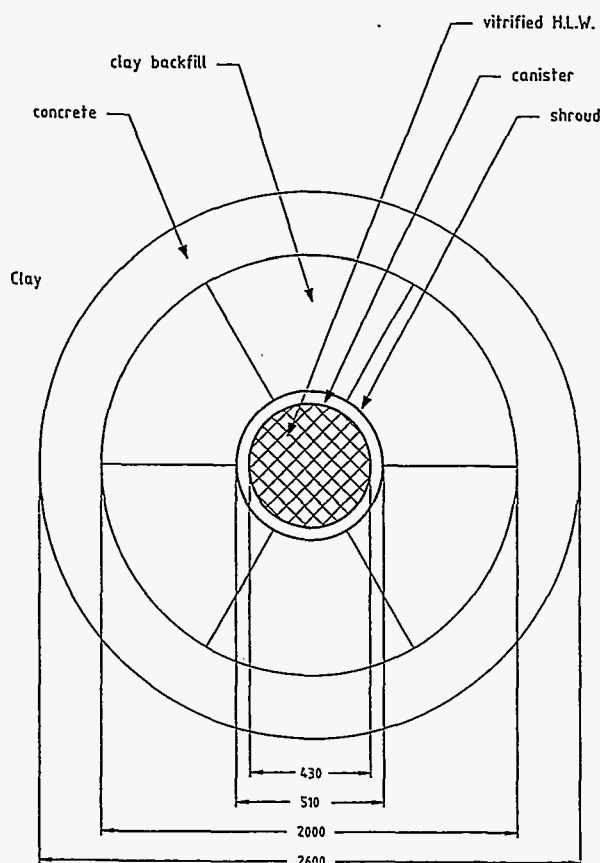


Figure 3.3. Detail of the Belgian reference concept for HLW (NIRAS/ONDRAF).

account the technical feasibility of the different components of the system, from the constructional and operational aspects to the assessment of the integrity of the volume of clay surrounding the disposal galleries. All the phenomena and processes involved in and around a deep geological repository (decompression, radiolysis, heat emission, gas production, etc.) and their evolution with time are dependent upon the waste types and the concept of the disposal infrastructure.

3.4.1 Research on Basic Phenomena

The safety of a repository for radioactive waste is conditioned by the long term behaviour of the various elements which constitute the engineered and natural barriers. Research on the basic phenomena expected to take place in the disposal system is therefore essential, in addition to the technical demonstration tests. Some of the research topics listed below are carried out in surface laboratories, others in the underground facility (URF). This research work is intended to better understand the

phenomena, which control the release of radionuclides from the waste packages, and their migration through the various successive barriers to the environment, in order to model these phenomena and validate the models. We are considering the following succession of research issues:

- characterization of waste packages and their compatibility with clay;
- geomechanical/geochemical behaviour of clay-based materials
- gas generation and transport;
- thermal, radiation and chemical effects; and
- radionuclide migration.

3.4.1.1 Characterization of Waste Packages and their Compatibility with Clay

Waste package is a general term used to indicate the conditioned waste in its container; the conditioned waste can be homogenous (vitrified waste, bitumenized sludge) or heterogeneous (e.g supercompacted waste in a cement matrix). "Container" is here considered as a generic term covering both the canister, into which the conditioned waste is loaded, and the overpack which has to provide isolation of the waste for relatively long time periods.

Background

Studies on waste packages performed at the SCK-CEN over the past 15 years have dealt with:

1. characterization of conditioned waste forms, as part of the national QA/QC programme (qualification of the processes, verification - Van Iseghem et al., 1990); and
2. compatibility with the anticipated disposal environment. These studies involved both laboratory and *in situ* "corrosion" tests. The efforts so far mainly focused on glass and bitumen waste forms, C-steel container material and, increasingly, on cement waste forms and stainless steel. These studies were aimed at characterizing the source term and at providing information for the future elaboration of acceptance criteria for the disposal of waste in the host formation.

Results

High-level waste glass (Van Iseghem, 1994; Lemmens et al., 1993). The results of *in situ* experiments are in agreement with those of laboratory tests which show

that glass is an efficient first barrier for the radionuclides; dissolution rates of less than 0.1 μm per year were recorded at an ambient clay temperature (16° C) in direct contact with Boom clay. However, the dissolution of glass is strongly enhanced by increasing the temperature and in the presence of clay, which acts as a sink for many glass constituents such as Si, rare earths and actinides. The long-lived actinides (Pu, Am, Np) in general leach slower than the bulk glass, and for more than 90%, the fraction leached is sorbed onto the clay. These data are further used in impact assessment studies reported under Section 3.4.3.

Bitumenized reprocessing waste (Berghman et al., 1990). A high leaching rate of NaNO_3 was noticed for Eurobitum, a reference Belgian bitumen, containing an average 35% of reprocessed sludge. By extrapolation, we can predict that a full size drum would be depleted in NaNO_3 (25%) within a few thousand years leading to the release of important amounts of nitrates into the near field. Lower leaching rates were noted for the actinides (Pu, Am); their leaching appears to be controlled by solubility and is not enhanced by lithostatic pressures.

Container (Cornelis and Van Iseghem, 1994). An average corrosion rate of 5 μm per year was inferred from *in situ* tests on carbon steel lasting up to 7.5 years; pitting processes with an average growth rate of about 20 μm per year are dominating. Corrosion proceeds mainly by pitting attack in the aerobic phase and congruent corrosion would dominate in the anaerobic phase. Stainless steel is becoming the candidate overpack material.

Future actions

Additional or corrective actions are required due to not following specifications, the absence of reference product specifications or representative samples (QA/QC programme).

Development, application and standardization of quality checking for waste packages must identify R&D requirements and coordinate the development of new test methods.

For HLW glass, further investigation of the secondary phase formation is needed since it could affect the glass dissolution mechanisms in the long-term.

Investigations on the soluble concentrations of the actinides in clay media in the presence of bitumen degradation products, on the ageing behaviour of bitum-

enized waste and on the microbiological degradation of bitumen due to nitrate and sulphate reducing bacteria are scheduled. Microbiological activity could lead to the production of methane and complexing agents which need to be further studied as gas and chemical effects.

A new laboratory corrosion programme (steel) will be run to provide the necessary information in both aerobic and anaerobic environments.

Chemical stability of Synroc, a titanate ceramic proposed as an alternative to glass, is under evaluation for Boom clay disposal environments.

New programmes on other waste forms, such as cemented reprocessing sludge (BR2/Dounreay), cellulose containing MOX waste, and spent fuel have to be started.

3.4.1.2 Geomechanical/Geochemical Behaviour of Clay-Based Materials

The mechanical and chemical stability of the near field provide a set of controlling factors for groundwater movement, radionuclide transport and heat dissipation through the interface between near and far field. The excavation disturbed zone in clay and the backfill/sealing material might substantially affect the subsequent migration behaviour of radionuclides.

Background

Excavation disturbed zone. The measurements of pore water pressure and stress distribution around boreholes and galleries during and after their construction (Neerdael and De Bruyn, 1988) have shown that the extent of the disturbance depends on the excavation diameter, the excavation speed and the oversizing with respect to the lining diameter; the magnitude of the disturbance drops significantly with distance and decreases slowly with time thanks to the plasticity of clay.

Backfill and sealing material. In case of a repository in clay, a clay-based material is chosen as backfill material for the same reasons as put forward when dealing with the geological barrier. Boom clay has been characterized with a view to reusing the excavated clay spoils for backfill, since oxidation (pyrite) can be prevented easily by fast drying. The following results have been found for highly compacted Boom clay with regard to compacted bentonite: (a) slightly higher but sufficiently low hydraulic conductivity, (b) lower swelling but still convenient regarding the lithostatic pressures at the Mol

site, (c) better retention properties for some radionuclides, and (d) steam effect less dramatic than for some bentonites.

When dry compacted clay is used as a backfilling around HLW packages, its behaviour during saturation is complicated by the thermal transient caused by the heat emission from the waste. It must be shown that during this transient period, no (negative) influence on the long term behaviour of the repository can occur due to e.g. shrinkage or collapse of the clay backfill. Therefore, the thermo-hydro-mechanical (THM) and geochemical behaviour of the backfill must be studied. Typically hydro-mechanical and thermo-hydraulic models have to be coupled to describe stress/strain behaviour, moisture migration and heat transfer. The thermo-hydraulic model also has to be coupled to a geochemical code to describe the migration and formation of chemical species.

To avoid the effect that the natural occurring, or human induced, disturbance in one disposal gallery would have on the entire repository, the disposal galleries need to be properly sealed from one another. The shafts must also be properly sealed because they might act as preferential pathways to the biosphere, short-circuiting the Boom clay formation.

The main requirements for a sealing material are: low hydraulic conductivity and long term mechanical and chemical stability. Clay is also the more preferable option in this case. With high density bentonite, the hydraulic conductivity criterion can easily be fulfilled and with a proper composition, the stability requirements can also be fulfilled.

Results

Excavation disturbed zone. Small changes in mechanical stress and pore water pressure have only a minor influence on the migration properties of the Boom clay. Large changes in stress and pore water pressure are limited to the zone close to the gallery or borehole wall.

Backfill and sealing material. A fairly extended database concerning THM properties of unsaturated clays is a prerequisite to enable physical model testing, model calibration and validation. Impressive work has been done on this subject during the last four years in the framework of three research contracts of the present E.C. programme (Volckaert et al., 1994). The results obtained confirm that swelling clays are promising

backfill materials.

Future actions

Potential influence of the stress changes on the migration parameters might be studied in combination with temperature, radiation and gas effects.

Quantification of the disturbed zone around a disposal gallery successively submitted to decompression and thermal loading is one of the main objectives of the PRACLAY demonstration test (see Section 3.3.4).

Efforts on the THM behaviour of dense unsaturated clay are continuing for the next five years. A large scale *in situ* demonstration test has been proposed within the next E.C. five year programme.

3.4.1.3 Gas Generation and Transport

In a radioactive waste repository, gas generation may occur due to several phenomena depending on a number of factors (waste types, packages, buffer/backfill, near field host rock). The gas release may increase the rates of flow of potentially contaminated groundwaters to the surface and two-phase flow may entrain radionuclides in solution at the gas-water interface.

Background

The main potential sources of gases in the case of deep geological disposal are methane from degradation of organic materials and hydrogen from anaerobic corrosion of iron. Of these gases, hydrogen is certainly the gas which can be released in potentially the largest amounts.

The objectives of the MEGAS (Modelling and Experiments on GAS migration in repository host rocks) project coordinated by SCK-CEN extend from the understanding of the consequences of gas generation to the validation, using a 3-D *in situ* gas injection experiment, of a gas migration model (TOPAZ-INTERA). Attention has to be paid to gas to ensure that the potential pressure build-up in the near-field of a repository would not lead to fractures in the host medium, which might act as new migration pathways affecting the long term safety of the whole disposal system.

Results

In the surface laboratory, special odometers were built to

saturate clay cores to measure its hydraulic conductivity and to perform gas injection; at the end of the gas flow experiment, the cores were still more than 95% saturated, as confirmed by X-ray tomographic analysis. The formation of preferential pathways and a low breakthrough pressure were observed during the field test. These observations are a consequence of the stress distribution around the test borehole. As explained in section 3.4.1.2 (excavated disturbed zone), the drilling of a borehole significantly reduces the stress close to the borehole wall and particularly the effective stress, i.e., the pressure keeping the clay particles together. As a consequence, it is relatively easy to create gas pathways in the excavation disturbed zone. Further *in situ* tests have shown that these fissures close very soon after the gas injection is stopped (Volckaert, et al., 1995).

Future actions

More experimental data are necessary to quantify the link between hydraulic and geomechanical parameters of Boom clay and further gas migration experiments are needed; the use of a swelling backfill material, which locally increases the lower effective stress distribution, would reduce the concentration of pathways in the excavated disturbed zone. Tests in the surface laboratory on larger clay cores will also contribute to increase confidence in the verification and validation of the model.

3.4.1.4 Thermal, Radiation and Chemical Effects

Radiolysis of water by gamma rays can lead to the production of oxidants which might seriously alter the near field chemistry and retention properties of the clay. The radiation effects need to be combined with heat effects, as they occur during the same period. Chemical species released from the waste might seriously alter the near-field chemistry and retention properties of the clay.

Background

The study of the combined effect of heat and radiation is one of the main objectives of the CERBERUS *in situ* experiment (Noynaert et al., 1992). The CERBERUS experiment simulates the in-floor configuration for the disposal of a COGEMA HLW canister after 50 years cooling. Instruments, or test specimens, have been installed in the periphery to obtain data on water chemistry, radionuclide migration, corrosion, radiolysis, water pressure and temperature distribution.

The thermal transient period will last about 300 to 500

years in the case of HLW and 3,000 to 5,000 years in the case of spent fuel. The formation of steam must be avoided at all times because it would lead to operational problems, enhanced corrosion, and could have a dramatic effect on the hydraulic and mechanical properties of clay backfill and sealing materials. A higher temperature will further increase the solubility of the waste form and radionuclides and might reduce the sorption capacity of the clay and/or increase the diffusion coefficients. These effects have not yet been quantified. The temperature cycle also has implications on the mechanical behaviour of the clay. The combined effect of all these influences on the migration in the near field is very complex to model; currently it can not be done with confidence due to a lack of knowledge.

Chemical effects have not yet been studied in detail; however some potential problems have already been identified. The presence of large quantities of degradable organic material and soluble salts, such as nitrates and sulphates, can have an important effect on the global near-field chemistry, the solubility of the radionuclides, and the sorption properties of the clay. The decomposition of e.g. cellulose could generate important quantities of complexing agents.

Results

Seven years of follow-up measurements in the clay around the CERBERUS experiment show a decrease in pH with about one pH unit and a very slight increase in redox potential so that the clay remained reducing. The presence of thiosulphates, which can seriously increase metal corrosion, and oxalate, which can act as a complexant, was observed (Put et al., 1993). The codes for the calculation of the thermal, hydraulic and radiation field were validated.

Selecting the appropriate concept, cooling time and overpack design allows one to avoid an investigation of high temperature and steam effects.

Future actions

Radiation effects will be further studied in the last phase of the CERBERUS experiment, together with the performance of a potential backfill material (Boom clay based) that has been submitted for more than five years to realistic temperature and radiation fields.

Chemical effects identified need further investigation, surely when elaborating acceptance criteria for geologi-

cal disposal systems. Irreversible complexation of actinides by small organic molecules would strongly increase their transport through the clay. Nitrates affect the redox conditions in the clay while high salt concentrations also influence its sorption properties.

3.4.1.5 Radionuclide Migration

Research on radionuclide migration through the Boom clay has provided data to support the performance assessment of geological waste disposal. Work was concentrated on methodological aspects, codes for flow and transport, theoretical studies, laboratory and field experiments on geochemical transport phenomena to develop and test conceptual and numerical models.

Background

Radionuclide transport in porous and fissured media is controlled by diffusion, advection, retardation (sorption, precipitation) processes and radioactive decay, as described in a general way by the advection-dispersion equation. In a rather stiff material, such as Boom clay, the radionuclide migration is dominated by diffusion. Advection plays a secondary role due to the very low hydraulic conductivity of this medium and the absence of preferential paths for the water (self-closure of fissures due to the clay plasticity).

Boom clay exhibits good sorption properties for cations due to its physico-chemical characteristics under *in situ* conditions. The presence of micro-dispersed pyrite and organic matter intimately associated with the clay mineral surface ensures strong reducing conditions while carbonate (calcite and siderite) maintains a slightly alkaline environment. These physico-chemical conditions are very favourable for the sorption of cations on the Boom clay surface.

From the performance assessment studies, three groups of radionuclides have been selected for further experiments in the present migration program:

- critical radionuclides: ^{14}C , ^{99}Tc , ^{129}I , ^{135}Cs and ^{237}Np ;
- less critical radionuclides: ^{79}Se , ^{93}Zr , ^{107}Pd , U-, Pu-, Am-, Cm-isotopes; and
- non-critical radionuclides used for the study of migration mechanisms in Boom clay (Sr^{2+} , Br^{-1} , HTO) are used as chemical analogues of relevant nuclides (Eu^{3+} as an analogue for the actinides).

The migration behaviour of radionuclides in the Boom clay is studied by means of different types of experi-

ments (De Preter et al., 1992):

- fundamental physico-chemical studies of radionuclides in the clay;
- laboratory experiments for the measurement on clay cores of the migration (and hydraulic) parameters (diffusion accessible porosity, retardation factor, diffusion coefficient etc.); and
- large scale *in situ* experiments for model validation and confidence building.

Mathematical models have been developed for the design and interpretation of migration experiments performed both on small scale samples and *in situ* at a larger scale. Different analytical models taking into account the various kind of experiments, the type of source terms and the boundary conditions are presently available to interpret laboratory migration experiments and to determine the migration parameters of the radionuclides. The tridimensional migration model and the values of parameters obtained in the surface laboratory on small clay plugs (3 cm) for HTO (tritiated water) have been validated on the metric scale (2 m) by comparison with model predictions from experimental results with large scale *in situ* injection of tritiated water.

Results and future actions

Running studies confirm that the most critical elements to be considered for long term safety are iodine and fission products.

Laboratory experiments have to be performed under strictly anaerobic conditions. A small exposure to traces of oxygen alters the physico-chemical characteristics of Boom clay; many radionuclides (Tc, U, Se, etc.) are very sensitive to oxidation. In the case of technetium e.g., the strongly sorbed TcO^{2+} cation is rapidly converted to the non-sorbed TcO_4^{-} anion if the oxidation potential of the interstitial solution increases too much.

Aqueous speciation, the clay surface properties, and the concept of anion exclusion or diffusion accessible porosity are fundamental in the migration of radionuclides.

Organic matter distributed between the solid phase (99.99%) and the interstitial solution (0.01%) plays a dual role in the sorption and the complexation processes of the trivalent actinides and lanthanides in Boom clay. The coating of organic matter at the Boom clay surface increases the surface complexation properties of the solid phase and enhances the retention of trivalent

radionuclides on the clay. On the contrary, small dissolved organic molecules might form soluble complexes with these nuclides increasing their mobility in water.

3.4.2 Demonstration Tests in Underground Research Facility.

The HADES underground research facility is presently the only one installed in a clay layer. The facility offers important opportunities for participation of foreign organisations and contributes to the scientific leadership of SCK-CEN for waste disposal in clay.

Objectives

Investigate and demonstrate the feasibility of disposal concepts for vitrified high level waste, long-lived waste and spent fuel and provide reliable data on the performance of repository barrier components; and allow testing and validation of models under representative conditions.

Research topics

The research carried out at SCK-CEN is related to the following scientific and technical aspects:

- testing and demonstration of disposal concepts;
- backfilling and sealing a repository;
- long term behaviour of repository components;
- ground water flow analysis and radionuclide migration; and
- monitoring the reconsolidation of the disturbed zone around an excavation.

All of these items were already introduced in Section 3.4.1. The corresponding demonstration tests now (or previously) running are briefly described below.

In disposal holes (in-floor concept), for demonstration purposes:

- a large scale integrated experiment simulating the radiation and thermal output of a COGEMA canister after 50 years cooling time (CERBERUS). Different experimental set-ups are installed in the periphery to get data on corrosion, migration, radiolysis and material performance; and
- full scale thermo-hydro-mechanical experiments under similar thermal conditions but according to other designs and instrumentation purposes and considering the use of several potential backfill materials (BACCHUS 1&2, CACTUS 1&2).

At the horizontal (in-gallery or axial concept), for validation purposes:

- large scale thermo-hydro-mechanical experiment (ATLAS), again under similar thermal conditions but without the use of backfill material between the clay wall and the heaters;
- 3-D gas migration test (MEGAS) using in-house designed injection and detection piezometers; and
- 2-D and 3-D radionuclide migration experiments using non-sorbed tracers (tritiated water, etc.)

The results of all these tests confirm Boom clay as a promising host rock for radwaste disposal.

In the framework of the fourth R&D programme on "management and storage of waste" of the E.C., we also developed two experiments for the French waste management authority (ANDRA):

- ARCHIMEDES project, now running for three years, aims at studying the acquisition and regulation of the water chemistry in a clay environment. The work programme consists of the following four main topics: (a) fluid and solid sampling and characterization, (b) *in situ* measurements, (c) microbial interactions; and (d) fluid-rock interaction modelling. Available results clearly show, e.g., that the microbial activity in the far field is at the limit of detection while the near-field exhibits the same microbial activity as a soil; and
- PHEBUS project aims at understanding the phenomenology of hydric exchanges between ventilated underground structures (operational phase) and the host clay. After support tests and mock-ups in surface laboratories, an *in situ* ventilation experiment has been installed from the URF and has been operational since May 1995.

An important action to be developed for the next ten years is the PRACLAY project. PRACLAY is a demonstration test simulating the thermal output of a 30 m long HLW disposal gallery, 2 m in diameter (see Section 3.3.4). The experiment will be installed from an extension of the existing facilities to be built over the next 3 years. The experiment is planned to last until 2005.

3.4.3 Safety Aspects of Waste Disposal

The tools needed for a preliminary evaluation of the safety of disposal of radioactive waste in Boom clay have been described. Performance assessment is a phased process and the models and data used have to be adapted as results from the R&D programme become

available.

This can be illustrated by the study on regional hydrology, which is above all one of the support research items for performance assessments. In the period 1981-1984, a regional site characterisation programme has been carried out. It consisted mainly of drilling about 20 boreholes located in northeast Belgium and the elaboration of pumping and slug tests to determine transmissivities and hydraulic conductivities in the aquifers. These boreholes have been equipped as piezometers and together with existing piezometers they form a regional piezometric network that consists of 122 observation points. The water levels in the piezometers have been measured monthly since 1984. However, most piezometers are located in the overlying Neogene aquifer. The scarcity of data from the underlying Ruisbroek-Berg aquifer is a considerable drawback for the hydrogeological modelling of the regional aquifer system and urgently needs remedial action to enable improvement of the available models.

Objectives

Develop and apply a comprehensive approach and methodology for evaluating the long term safety of disposal in clay, including radiological as well as non-radiological (chemical-toxic) consequences for the purpose of increasing confidence in building and public acceptance by putting the long term risks into perspective.

Background

A performance assessment of a geological repository for radioactive waste disposal consists of three steps:

1. identification of scenarios that can lead to exposure of man and an estimation of the probability of occurrence of these scenarios;
2. evaluation of the radiological consequences of the identified scenarios; and
3. comparison of the estimated doses and risks using appropriate radiological protection criteria.

Since no criteria or guidelines applicable to radioactive waste repositories have been published in Belgium, the recommendations of the International Commission on Radiological Protection (ICRP) are used as a reference. The ICRP recommends the application of a total dose limit to individuals from all relevant sources. The annual effective dose limits are 1 mSv/a for a member of the public and 20 mSv/a for occupational exposure. These limits are considered by ICRP as the boundary between

"unacceptable" and "tolerable". Concerning potential exposures, ICRP recommends that risk limits be of the same order of magnitude as the risks corresponding to the dose limits for routine exposure.

In order to meet the requirements of individual dose or risk limits for all relevant sources, ICRP proposes to determine dose or risk constraints related to sources. In several European countries, e.g. Switzerland, the dose constraint has been taken equal to 1/10 of the annual dose limit for the case of geological repositories. We recommend using the same value in Belgium. This dose constraint of 10^{-4} Sv/a is clearly indicated in the diagrams reproduced in this section. The corresponding risk constraint is of the order of 5×10^{-6} /a for fatal radiation induced cancers.

A difficult aspect of performance assessment is the time scales that have to be considered. In France, the radiological protection authority requires forecasts of doses based on an explicit uncertainty analysis for the first 10,000 years. For a period of 100,000 years, the impact of expected changes in climate on the repository system have to be taken into account. For very long time scales, "more qualitative assessments have to be made to verify that the release of the radionuclides does not result in an unacceptable individual dose."

Results and future actions

Hydrogeological modelling. A new version of the regional hydrogeological model for the Mol site (Wemaere and Marivoet, 1995) has been achieved by considering the available data and computer techniques and after reviewing all the improvements that could be brought to the model developed in 1985. A detailed geometry is used to reproduce the geological structure in the model, and special attention is given to the fault system in the northeastern part of the modeled area. The calibration of the regional model, which was strongly hindered by the poor characterization of the underlying aquifers, led to a value of 3×10^{-10} m/s for the hydraulic conductivity of the Boom clay on a regional scale. This means that the calibrated value is much higher than the values measured *in situ* or on cores taken from the underground laboratory (3×10^{-12} m/s). This discrepancy should be further investigated. The latter value is used for the clay migration model in the performance assessment, because in that model a local value of the hydraulic conductivity for clay is needed.

Additional hydrogeological investigations focusing on the spatial variability of the parameters of the Boom clay and on a better characterization of the aquifers,

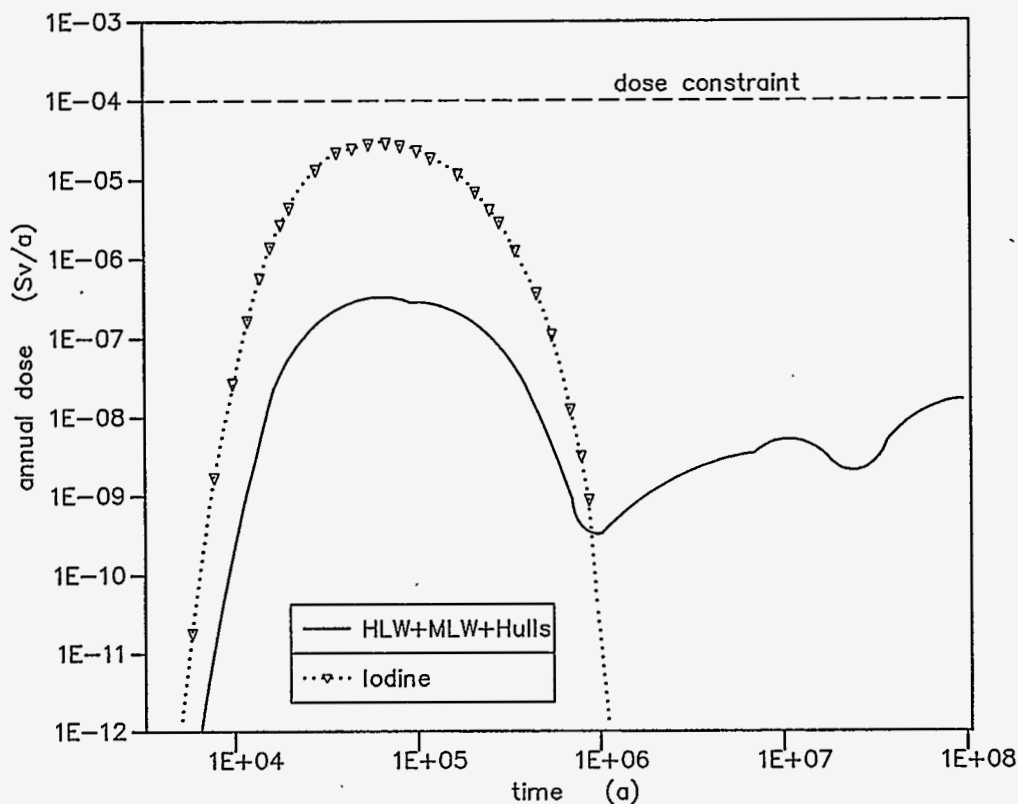


Figure 3.4. Normal evolution scenario - Annual doses via the water well pathway.

especially the deepest ones, underlying the Boom clay are highly recommended. Further, the hydrochemistry should help to understand the behaviour of the aquifer system and constrain its modelling since stable isotope analysis and major trace element analyses provide a way to understand the origins of the water and its evolution.

Performance assessments of reprocessing waste. Following the CEC's PAGIS and PACOMA studies, the "Updating 1990" study (Marivoet, 1992) was performed. A normal evolution scenario, which considers all phenomena that are certain or highly likely to occur, as well as some altered evolution scenarios (deep water well, climatic change, tectonic fault) have been identified in this way. Because the Neogene aquifer is an important drinking water resource, the pumping of drinking and irrigation waters from a well located in that aquifer is considered as a realistic pathway to the biosphere within the normal evolution scenario. The consequences calculated in the case of this scenario for various considered waste types are shown in Figure 3.4. For the reference waste types (HLW, hulls and MLW) together, the highest calculated annual doses, which are only 3×10^{-7} Sv/a, are due to the small fractions (about 1%) of I-129 present in the hulls and the medium-level

waste.

The deterministic performance calculations are complemented with stochastic calculations in which the uncertainties in the model parameters are taken into account. The results of such calculations show that the expected value for the annual dose and the 95% percentiles also remain below the dose constraint. Figure 3.4 also indicates that a possibly problematic waste type consists of the iodine waste. This waste type is not included on the list of waste types that have to be considered in Belgium (NIRAS, 1989). This waste arises in the reprocessing plants from the capture of iodine from the dissolver gasses and contains 98% of the I-129 which is generated by nuclear fission. Since iodine is not sorbed on the Boom clay, the disposal of this waste form might, in case all of it were returned to Belgium, lead to some scenarios for annual doses of the order of the dose constraint.

In 1991, the CEC's EVEREST project was started. Complementary sensitivity studies are investigated within EVEREST to determine which elements of the repository system strongly influence the performance of the repository system. Stochastic calculations were per-

formed to assess the influence of the uncertainties in the model parameters on the calculated annual doses. Other sensitivity studies focused on conceptual model uncertainty in the aquifer modelling and on uncertainties in the scenario descriptions.

In 1992, the next Belgian performance assessment, ordered by NIRAS/ONDRAF, started with the description of a systematic scenario study. Recently two additional scenarios have been analysed (Wibin and Marivoet, 1995). The exploitation scenario considers the pumping of water from the Ruisbroek-Berg aquifer which underlies the Boom clay layer. The consequences associated with this scenario are more than two orders of magnitude higher than the doses estimated for the normal evolution scenario in which only pumping from the overlying aquifer was considered. The "poor sealing" scenario considers that the sealing of the transport gallery and the access shaft are not successful. The consequences of this scenario are not much higher than the ones estimated for the normal evolution scenario.

The next step will be a detailed analysis of the normal evolution scenario. In this analysis, all phenomena which are about certain to occur will be considered. Thus, the expected evolution of the climate for the next

100,000 years has to be taken into account. The impact of the climate changes on the aquifer system will be evaluated by applying geoprospective methods. In this time period, two glaciations are expected to occur that will result in drastic changes in the geography and shallow geology. Consequently, the uncertainties in the aquifer system become considerable for these time scales. However, it should be noticed that these climate changes will have very little influence on the migration of radionuclides in the Boom clay, which is about 32 million years old and would remain stable for another million years.

The case of spent fuel. SCK·CEN started a preliminary performance assessment of the direct disposal of spent fuel in a clay layer (Marivoet et al., 1995). The spent fuel types considered are uranium oxide fuels with burn-ups of 33 and 45 MWd/tHM and MOX fuel with a burn-up of 45 MWd/tHM. The radionuclide inventories have been calculated with the ORIGEN2 code. A serious problem in the assessment is that no information is available from specific experiments on the behaviour of spent fuel in conditions similar to the ones prevailing in a repository in clay. Therefore, the near-field model is largely based on results obtained from research programmes (mainly Canadian and Swedish), on the dis-

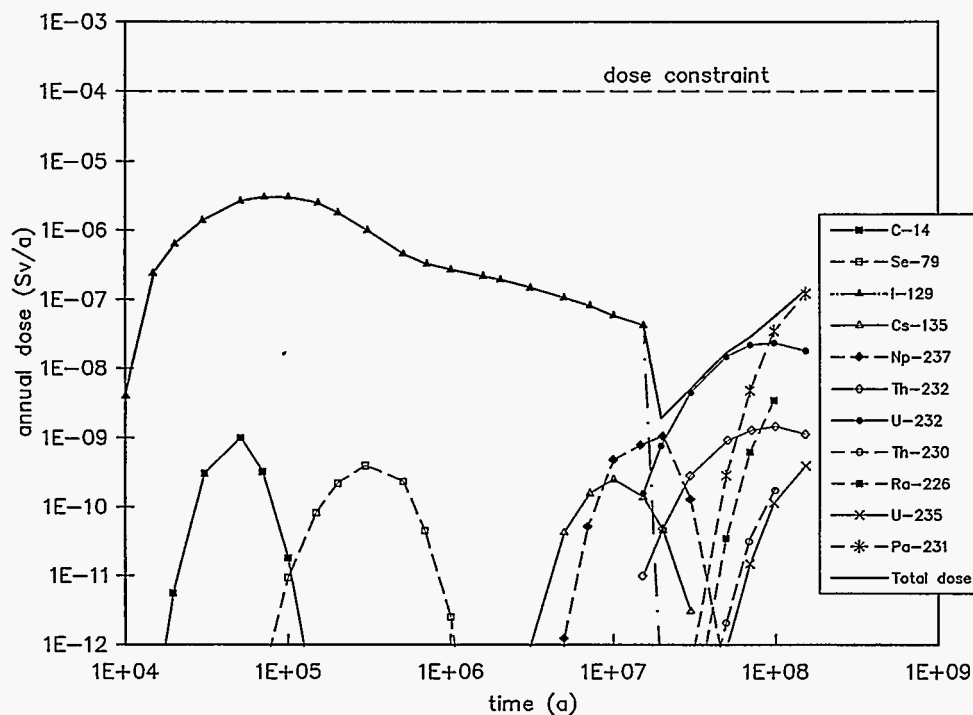


Figure 3.5. Preliminary performance assessment of the direct disposal of spent fuel in clay. Calculated annual doses via the water well pathway (normal evolution scenario).

posal of spent fuel in granite.

The annual doses calculated in the case of the normal evolution scenario are given in Figure 3.5. The maximum calculated annual dose is due to I-129 and should occur about 60,000 years after disposal. The maximum annual dose actually depends on the fraction of iodine which is present in the gap between pellets and zircalloy hulls (about 10%). The bulk of the iodine (90%) is dissolved in the uranium oxide crystals and is released over a 10 million year period. A second but lower dose peak due to actinides is expected to occur after a very long time period (several tens of millions of years). The preliminary assessment shows that, from a radiological point of view, the direct disposal of spent fuel in a clay layer is an acceptable option.

Chemical toxicity aspects in the R&D geological disposal programme. A preliminary assessment of the chemical toxicity aspects, related to the geological disposal of radioactive waste, has been carried out. A number of simplifying assumptions have been made for this assessment, and the study considered only the possible toxicity of heavy and other metals present in the waste forms or the packing materials. The elements that caused the highest concentrations in the overlying aquifer were uranium, molybdenum and nickel. However these concentrations are lower than the concentration limits given in a European guideline for water to be used for drinking water purposes. The calculated low concentrations can be attributed to the low solubilities of some metals and the fact that most of the expected species in solution are cations, which are strongly sorbed on the Boom clay.

However, this assessment is still preliminary. For many essential parameters like solubility limits and retention coefficients, rough estimates had to be used in the simulations because no experimental data were available. The consequences of beryllium, which arises from the beryllium matrices of SCK-CEN's research reactor BR2, were not analysed because beryllium is essentially toxic to the lungs; therefore, the analysis requires the application of a detailed biosphere model to assess the consequences of the inhalation of beryllium.

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CHAPTER 4

THE PROBLEM OF SITE SELECTION FOR A RADIOACTIVE WASTE REPOSITORY IN BULGARIA

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Abstract. The approach to the solution of the problem of site selection for the construction of a high level radioactive waste (RAW) repository in Bulgaria has passed so far through two stages. The first stage includes the regional survey of the country on a 1:500,000 scale to select regions with suitable conditions for further investigations. At the second stage, 18 sites have been selected in these regions, to be subjected to more detailed analysis. Two types of areas, providing comparatively favourable conditions, are considered in the present work: the marl terrains in north-west and northeast part of the Fore-Balkan in north Bulgaria, and the Sakar granite pluton in southeast Bulgaria. The marls are clayey and have a thickness of up to 1000 m. They are situated in a zone of calm tectonics and seismicity of VII-VIII degree on the MSK scale. All available data for the Sakar granite pluton are also favourable. Additional *in-situ* and laboratory investigations have to be carried out for both types of formations with the view of collecting the necessary specific information, required for the in-depth RAW disposal.

4.1 INTRODUCTION

The Bulgarian Nuclear Power Plant (NPP) of "Kozlodui" is equipped with 6 nuclear reactors of the VVER type (produced in Russia) and has an output of 3760 MW of electric energy, which is 35 - 40 % of the total output of the country. The construction of the second Nuclear Power Plant of "Belene" has been stopped because of civil protests.

So far, the unsolved problem of radioactive waste (RAW) processing and storage is one of the reasons for the negative social reaction and for the attitude of ecological organizations against nuclear power generation. Vast quantities of unprocessed low and medium level wastes have been accumulated after nearly twenty years of operations at the Kozlodui NPP. Their total volume at the closing of the plant is estimated to be from 128,000 to 170,000 cubic meters in the cemented state.

The problem with the highly radioactive wastes is still more serious. During the last several years, Russia refuses to further process the waste fuel, which is now stored at a temporary repository. Negotiations are in progress for the signing of a new agreement, according to which the vitrified highly radioactive wastes obtained after the spent fuel processing are to be returned to Bulgaria for final disposal. In case that such agreement

is not achieved, the spent nuclear fuel will be stored for several decades at a temporary repository in Kozlodui. In 1991, the Council of Ministers of the Republic of Bulgaria imposed the task of developing a concept for the construction of a national RAW repository on the Bulgarian Academy of Sciences (BAS) with the view of accelerating the solution of the problem. A large team of scientists from the Earth Sciences Division of BAS was organized to study foreign experience and to make a thorough analysis of the natural environment in Bulgaria. As a result, areas and geological complexes that appear favorable for further investigations concerning the construction of RAW repositories have been determined (Milanov et al., 1993).

The problem of selecting sites and rock systems, suitable for highly active RAW has been carried out in two stages. A preliminary screening of the territory of the country has been performed, and single regions distinguished where suitable geological formations are expected to be found. A subsequent screening has been carried out in these regions to select 18 sites offering considerably better conditions.

4.2 PRELIMINARY SCREENING OF THE TERRITORY OF THE COUNTRY

The territory of Bulgaria has a complex and diverse geo-

logical structure. Part of it is affected by young Alpine tectonics and is characterized by complex and difficult geological conditions from the point of view of the problem to be solved.

Rocks and formations ranging in age from the Precambrian to the Quaternary make up the geological structures of the country. The metamorphic and magmatic complexes are distributed mainly in south Bulgaria: the Rhodopes massif, the Sredna Gora and the Sakar-Strandzha zone, and the sediment complexes in the region of the Balkanides, the Kraishte and in the Moezian platform. The volcanogenic sediments and volcanic complexes are well developed in the Sredna Gora (of Upper Cretaceous age) and in the Rhodopes massif with Paleogenic formations (of Oligocene-Miocene age) situated on its periphery.

The Bulgarian territory falls entirely within the region of the Alpine-Himalayas orogeny (Boncev, 1971) and this is the prerequisite for the relatively complex tectonic conditions. Deformations were established which are related to the Precambrian mega stage in the development of the highly metamorphic complexes as well as the Caledonian Variscian deformations, early and late Alpine deformations and the neotectonic deformations related to rock complexes of the Phanerozoic mega stage.

The superposition of various tectonic movements in the course of time has led to the formation of folded structures, varying in type and magnitude, and terrains of block or block/thrust structures. The rock complexes in them are strongly deformed and have hydrogeological and geotechnical engineering conditions which are difficult to model. This especially concerns the Balkanides, the Kraishte, the Strandzha zone and parts of the Rhodopes massif. Fault zones exist in these morphotectonic units, along which neotectonic movements of an amplitude of up to 3400 m occur, accompanied by rock deformations and the development of exogenic geological processes.

The selection of zones with low tectonics, from the Neogene to the present, and containing suitable rock complexes is facilitated by the carefully studied geology of the country. The whole territory of Bulgaria is presented on geologic, tectonic, engineering geology and hydrogeology maps on scales from 1:10,000 to 1:1,000,000. A map of the geologic hazards in Bulgaria has recently been published on a scale of 1:500,000 (Iliev et al., 1994). The new geologic map of Bulgaria on the scale of 1:100,000 has been very useful for the

geologic screening of the country. It is based on the lithostratigraphic principle and provides a very good idea for the distribution, composition and structure of rock complexes. There is also available information for the in-depth structure of the lithostratigraphic units, which provides a means of choosing rock complexes of great thickness and suitable properties (granites, gneisses, volcanic rocks, serpentinites, marls and clays. Evaporitic rocks have not been considered since they are of industrial interest or are situated at great depth.

The geological analysis of the country has been supplemented by analyses from the other earth sciences. The lithostratigraphic information, combined with data from tectonic and seismic investigations, has provided the possibility of delineating zones of relatively less tectonics, where the number of active faults is smaller and the seismic centers are of smaller magnitude. The seismic characteristics of the Balkans peninsula and Bulgaria are reflected by a series of maps, showing locations of strong earthquakes up to 1990 with the magnitude-depth distribution, the possible epicenters of strong earthquakes, the seismic risk for a period of 1000 years, etc. The specificities of the temperature regime and of the geothermal field are also taken into consideration.

The contribution of engineering geological analysis consists of information about the texture and structure of the rock massifs, the physical, mechanical and chemical properties, and the conditions for the construction of underground openings in them.

The hydrogeological conditions in Bulgaria are summarized in maps of different scale, which provide information about the groundwater basins, their water transmissibility and rock filtration properties. Vast regions of the country have been excluded from further consideration on the basis of the available hydrogeological information, proving that RAW disposal in them is impossible.

The geographic analysis has taken into account the relief characteristics, the hydrographic network, the climatic specificities, the natural resources, the economic-geographic and conditions of population. A map has been created on the basis of the density of population, the network settlements and the average distance between settlements, on which five types of regions are distinguished from the point of view of the problem to be solved. The possibilities of utilizing about 260 mines for disposal purposes have been studied separately, and a selection has been made for the most prospective sites. The comparison and juxtaposition of the results of these

different earth sciences have led to the selection of regions offering the best conditions for investigating a site, suitable for the construction of a RAW repository. On this basis, a "Map of Categorization of Terrains in the Territory of Bulgaria" has been prepared on a scale of 1:500,000. A reduced copy of this map is presented in Figure 4.1.

The categorization has been performed on the basis of the following principles:

- All natural conditions of the country are considered but priority is given to the geological conditions;
- Preference is given to those regions where positive assessments of the geologic, seismic-tectonic and hydrogeological conditions coincide and the other conditions are not negatively assessed;
- Except for natural conditions, other factors are taken under consideration too—technogeneous loading,

demographic conditions, ecological conditions, interests of tourism, etc.

The regions possessing favourable characteristics are concentrated mainly in the northwest and northeast parts of the country (Fig. 4.1). They contain: (a) rock complexes of considerable thickness and surface distribution; (b) no active faults; (c) level of seismicity that is lower than the VII - VIII degree according to the 1000 year map; (d) hydrogeological conditions that are acceptable; and (e) a density of population that is not too great.

4.3 METHOD FOR SELECTING SUITABLE SITES

The next step in the procedure of site selection has been to distinguish several tens of areas and mines in the regions with favourable conditions, where comparatively good geologic settings exist for the in-depth disposal

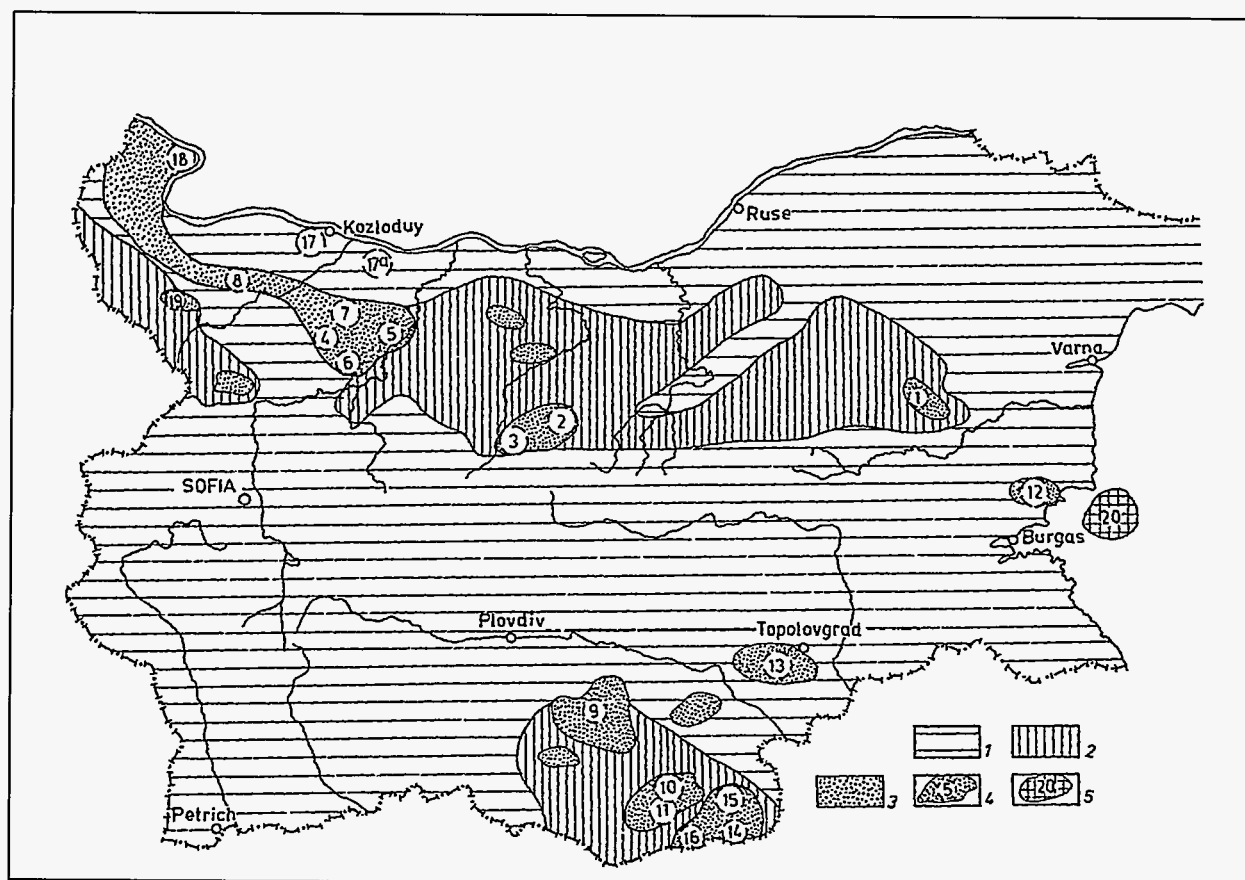


Figure 4.1. Map showing categorization of the Territory of Bulgaria into: (1) site unsuited for RAW repository construction; (2) prospective sites for further investigations; (3) regions with selected single sites for additional investigations; (4) a particular numbered site; and (5) a tunnel in the Black Sea offshore area (after Kostadinov and Kozhoukharov, 1992).

of highly radioactive wastes. Their number has been reduced to 18 by the method of successive elimination. The selected 18 sites have been investigated in more detail on the basis of the available information and minimum additional investigations. A report has been prepared for each of the sites, summarizing the geology, hydrogeology and engineering geology information. The reports are supplemented by detailed geologic maps and lithostratigraphic profiles.

The comparative analysis of the sites is performed on the basis of the criteria proposed by the special commission of the EC countries (European Catalogue 1979, Orłowski and Shaller, 1990), taking into consideration the specific conditions in Bulgaria. The criteria have been divided in four groups: (a) rock-linked parameters; (b) basic formation parameters; (c) formation - environment factors; and (d) supplementary selection factors. The rock-linked parameters include the rock's sorption capacity, thermal conductivity and solubility. The formation is evaluated by a larger number of parameters: thickness, minimum depth, surface area, homogeneity and uniformity, permeability and geotechnical properties. The environment in which the formation exists is evaluated by three important factors: hydraulic gradient, seismicity and tectonics. The additional factors include: the availability in the region of a rock formation and its potential use for economic purposes, the sensitivity of the zones to climatic and hydrologic changes and socio-geographic and population conditions.

The sites have been classified according to their suitability on the basis of an ordinary expert analysis, as well as by means of a system analysis (Vachev and Evstatiev, 1994). Priority scales have been developed for each criterion for the purposes of system analysis.

This classification has a preliminary character because the available information on the most important criteria such as sorption of the rock, its filtration properties and the hydraulic gradient, are insufficient for quantitative assessment. However, the sites composed of Lower Cretaceous marls in the Fore-Balkan, the Sakar granite pluton, and the gneiss and serpentinite massifs in the East Rhodopes, although at a preliminary stage, have been determined as the most favorable for further investigations.

4.4 CHARACTERISTICS OF SITES

Examples of prospective disposal sites from two different areas are presented in order to show the degree of investigations and the completeness of the available data

at the conceptual stage. The first area is situated in north Bulgaria and consists of thick marl complexes, and the second is in south Bulgaria in the Sakar granite pluton.

4.4.1 Prospective Sites in Lower Cretaceous Sediments of Fore-Balkan

A vast depression was formed in the Fore-Balkan of north Bulgaria during the Lower Cretaceous where sediments, mainly of marl composition, are deposited (Nikolov and Khrishev, 1965). These sediments have been carefully investigated at the surface and at depth during explorations for oil and gas deposits, and their tectonic conditions and lithostratigraphic structure have been studied in detail (Nikolov et al., 1991). They have been subjected to additional analysis in three reports which are supplements to the Concept of BAS for a National RAW repository (Nikolov and Ruskova, 1992, Monov, 1992, 1993).

The information presented below is obtained from these reports. The results from the analysis show that several sites situated in northwest and northeast Bulgaria are most favorable for more detailed future investigations. These sites contain comparatively pure clayey marls of great thickness, up to 1000 m and more. The marls in central north Bulgaria contain thick accumulations of limestones and sandstones. Some of them are water-bearing, and for this reason are excluded from further consideration.

4.4.2 Prospective Sites in Northwest Bulgaria

Several sites situated between the Iskar and Ogosta rivers fall into this category (sites Nos. 4, 5, 6, and 7 in Fig. 4.1). They are situated at a distance of 60-80 km south of the Kozlodui NPP. They are in the northern strip of the west Fore-Balkan, which is characterized by relatively calm neotectonics. Intensive tectonic activity had ceased after the Pyrenean phases, when the Fore-Balkan was formed. There are no active faults in the vicinity of the sites. The seismicity is of the VII degree on the MSK scale for a period of 1000 years.

Gas deposits have been discovered in the region, and as a result, there are more than 150 deep boreholes. This has provided data for lithostratigraphic and geophysical investigations and the investigation of geological structures both at the surface and at depths down to 3500 m (Fig. 4.2).

The Sumer and Mramoren formations which consist of

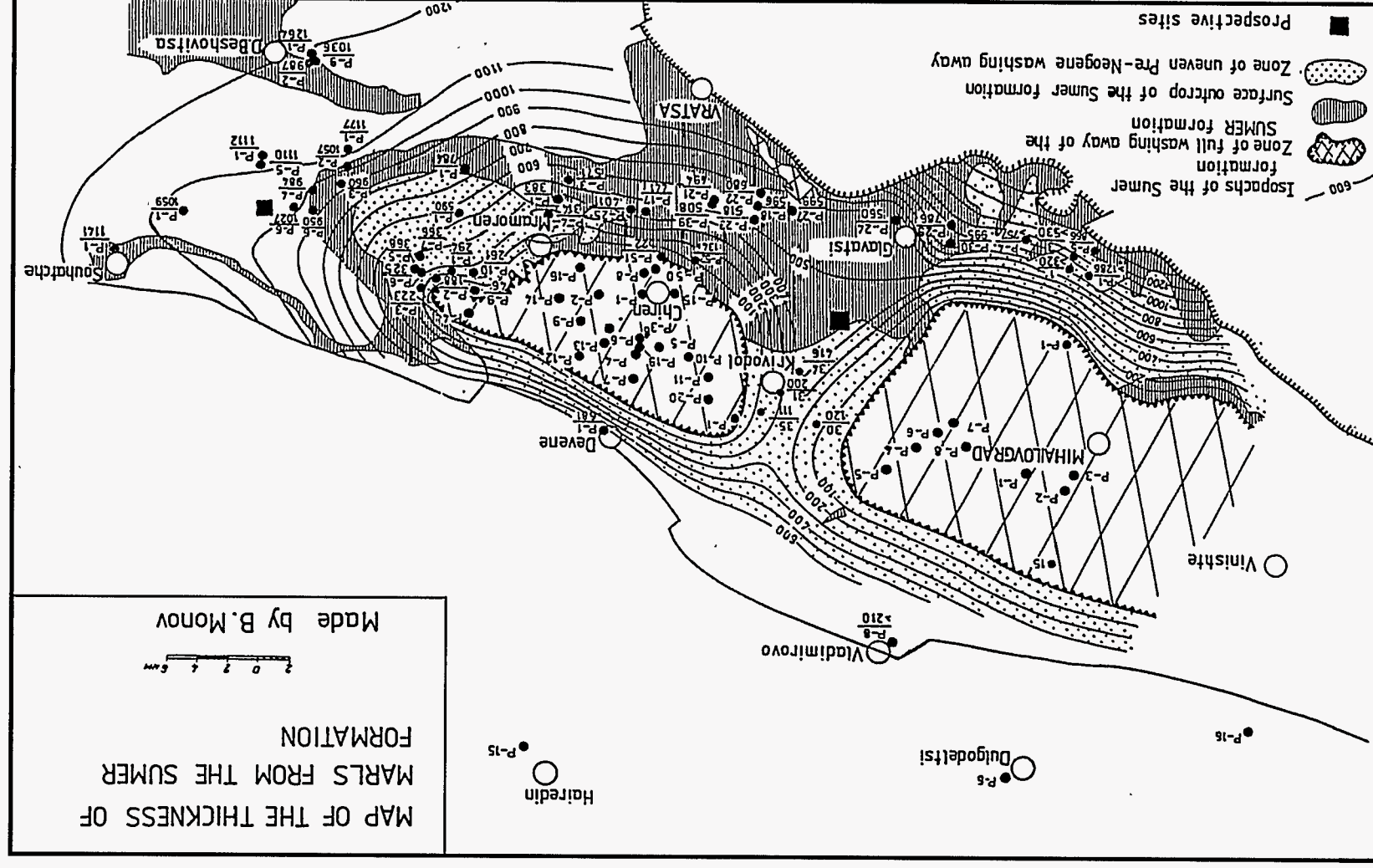


Figure 4.2. Map of the thickness of marls of the Sumer Formation (after Monov, 1993).

very thick clayey marls are of greatest interest from the point of view of the construction of an in-depth repository (Fig. 4.3). The available hydrogeological data indicate that the marls are dry and of very low permeability.

4.4.3 Prospective Sites in Northeast Bulgaria

The Gorna Oryahovitsa formation, in the Lower Cretaceous sediments of northeast Bulgaria, is most interesting as a prospective site for RAW disposal (Nikolov et al., 1991). The formation consists of Lower Cretaceous clayey marls where terrigenous intercalations are almost absent (Figs. 4.4 and 4.5). The selected site (No. 1 in Fig. 4.1) near the village of Zlatar, Shoumen district, is situated in a shallow anticline and is characterized by a low level of neotectonics and lack of active faults. The marl thickness exceeds 600 m. The Ticha formation, which is a buffer zone also containing thick marl layers, occurs in the Gorna Oryahovitsa formation (Fig. 4.5). The seismicity of the region is of VIII degree on the MSK scale according to the seismic map for a period of 1000 years.

The Concept of BAS accepts marl terrains as possibilities for both in-depth disposal of high level RAW and the surface-type repository for low- and medium-level RAW. From the point of view of problems related with the attitude of the population concerning the RAW repository, it is advantageous to build repositories for both types of waste at one and the same place.

Two types of repositories are proposed for consideration for in-depth disposal of high level RAW: (1) mine disposal and (2) borehole disposal. The comparatively small volumes of this type of waste make it possible to consider the construction of the second type of repository, which is less expensive and possesses certain technological and ecological advantages. Moreover, considerable experience exists in Bulgaria on the performance of deep boreholes, in marl rocks, in relation to the exploration for oil and gas deposits.

4.4.4 Prospective Sites in Magmatic-Metamorphic Terrains

Several sites with magmatic and highly metamorphic rocks in southeast Bulgaria are proposed in the Concept of BAS. The following sites have been selected after comprehensive analysis of natural conditions in this part of the country: the Byala Reka structure, composed of Precambrian highly metamorphic gneisses; the Avren

and Zhâlti Chal sites, composed of metaultrabasites; the Sakar site, composed of Paleozoic granites and two sites in the East Rhodopes Paleogene depression, composed of volcanic and volcanogenic sediments (Nos. 9, 10, 11, 13, 14, 15 and 16 in Fig. 4.1). Preliminary explorations on these sites have been performed by Kozhoukharova (1992), Kozhoukharova and Kozhoukharov (1992), and Kozhoukharova, et al. (1992).

4.4.5 Prospective Sites in Paleozoic Granites of Sakar Pluton

The Sakar site in southeast Bulgaria (No 13 in Fig. 4.1) is entirely within the area of the mountain of the same name. The region is composed of Precambrian high-crystalline metamorphites, Paleozoic metasediments and granites, Triassic metasediments and Pliocene formations (Kozhoukharov et al., 1994a, b). From a tectonic point of view, the region falls into the range of the Sakar unit, which is a component of the Sakar-Strandzha tectonic zone. About 60% of the site is composed of Paleozoic granites, known as the Sakar pluton. At the surface, the granites have been well investigated, but there are no data about their condition at depth. There are no active faults in them from the neotectonic stage; faults of this type are observed along the periphery of the mountain beyond the limits of the pluton. The seismicity is of the VII degree on the MSK scale for a period of 1000 years.

4.4.6 Characteristics of Sakar Pluton

The Sakar pluton was emplaced entirely among the Precambrian high-crystalline, ortho- and para-metamorphites of the Prazhodopian supergroup (Kozhoukharov, 1984, 1987) with presumed age of Archaic (?) - Lower Proterozoic. It intrudes and is partially metamorphosed by contact with the porphyric blastic migmatites of the Pânovo formation, the different gneisses, gneiss-schists and schists, amphibolites, graphite- and iron-bearing quartzites, etc., of the Zhâlti Chal variegated formation as well as the metaconglomerates of the Konstantinovo formation. A multitude of xenolites of these rocks occur in the peripheral parts of the pluton. At its western end, the Sakar pluton crosses and contact metamorphoses Upper Carboniferous sediments. The basic varieties of the granitoids in the Sakar batholith are three: uniformly grained; porphyric and porphyroid and aplitoid-pegmatoid (Alexandrovo) granites.

The porphyric granites are found in the western parts of

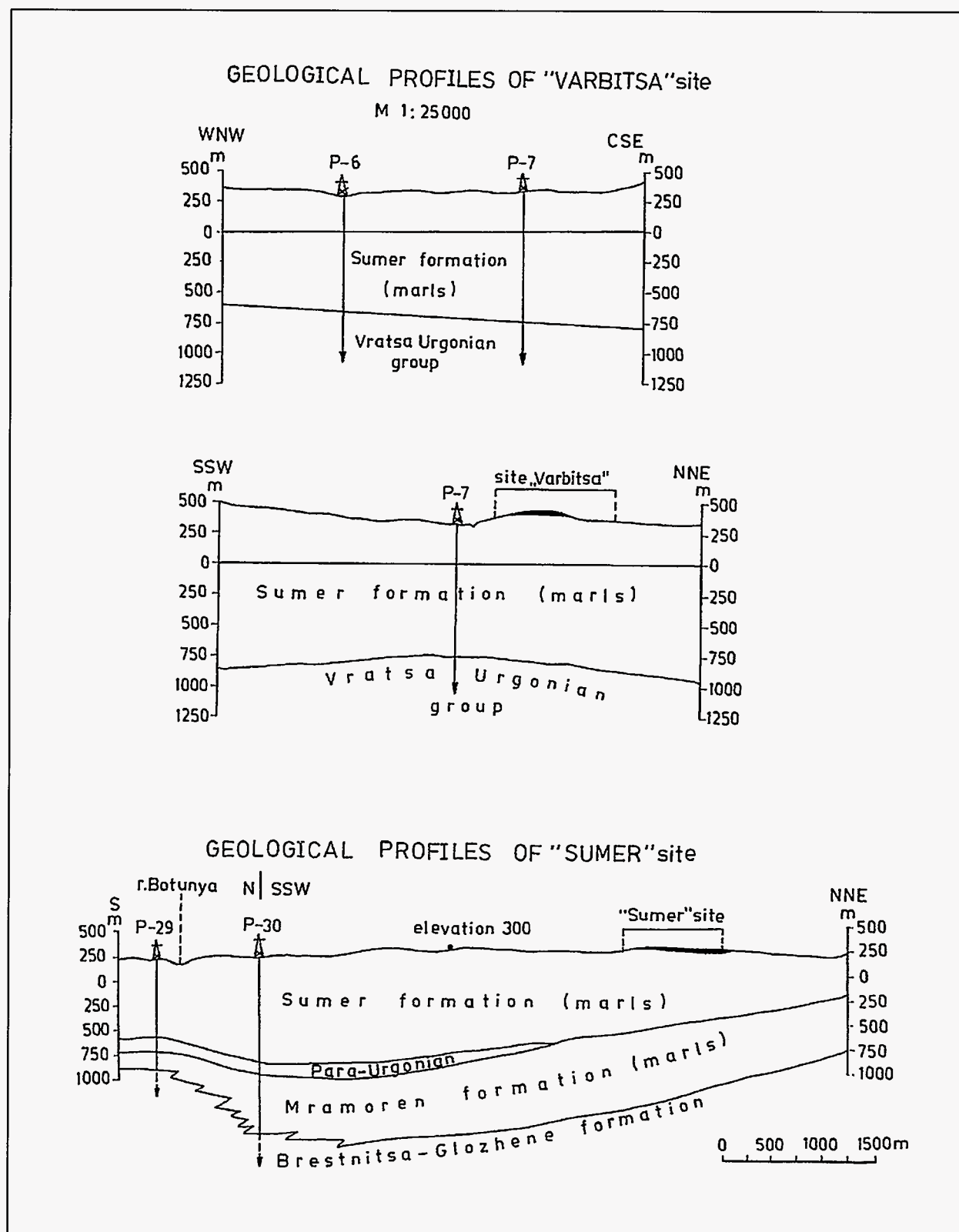


Figure 4.3. Geological profiles of the "Varbitsa" and "Sumer" sites (after Monov, 1993).

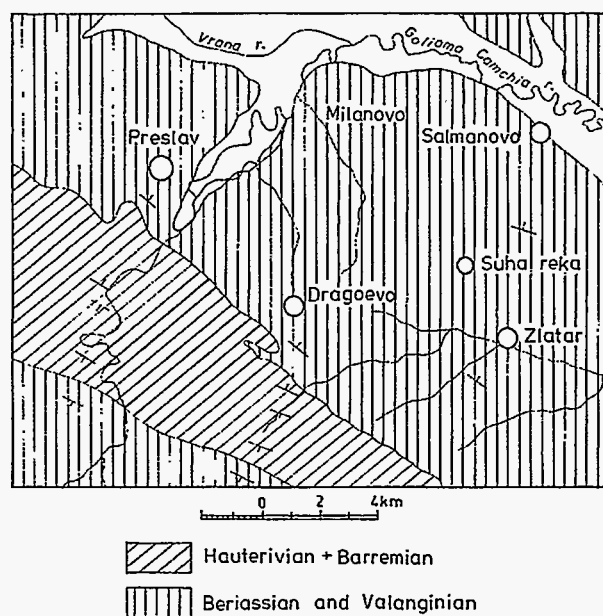


Figure 4.4. Geological map of the Zlatar site (after Nikolov and Ruskova, 1992).

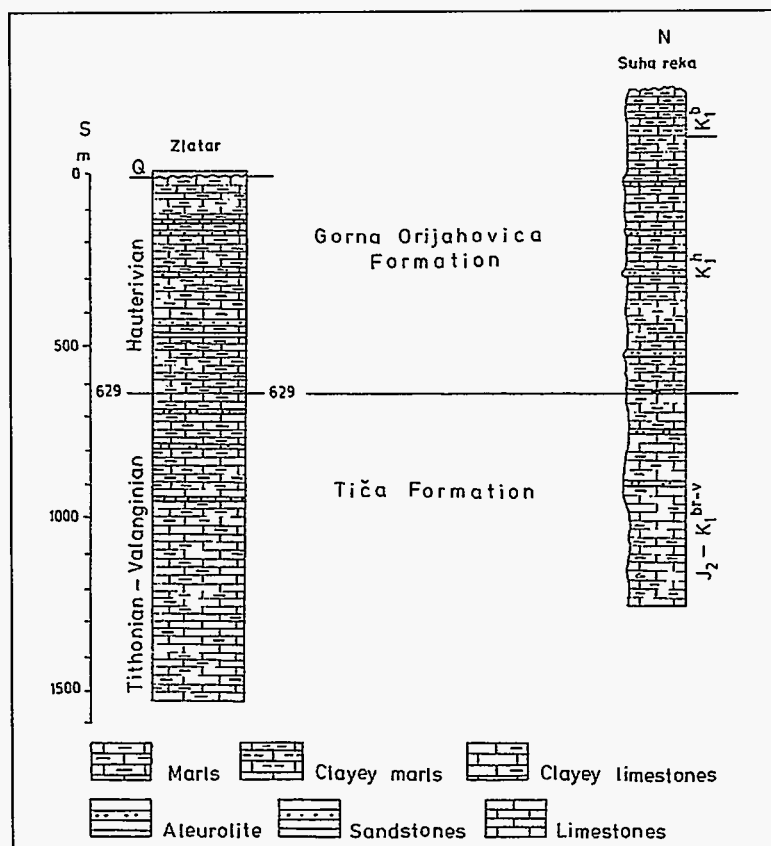


Figure 4.5. Lithostratigraphical columns of the Zlatar site (after Nikolov and Ruskova, 1992).

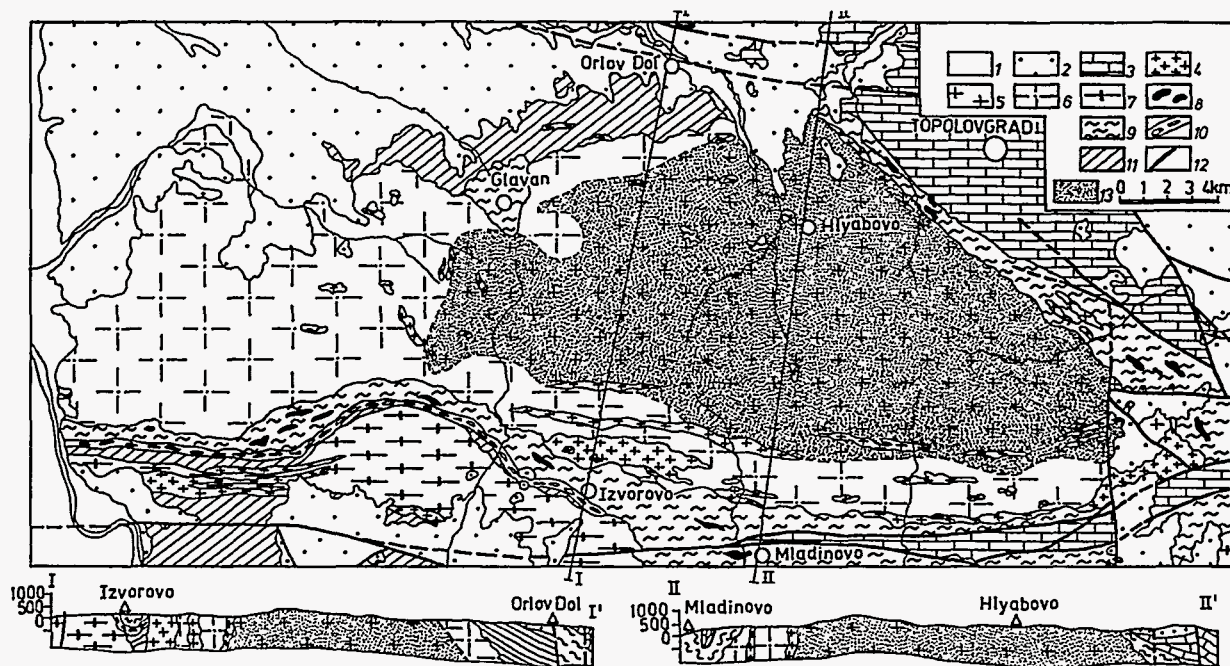


Figure 4.6. Geological map of the Sakar pluton: 1 - Quaternary; 2 - Pliocene sediments; 3 - Upper Paleozoic and Triassic metasediments; 4 - leucocratic (Alexandrovo) granites, Sakar pluton; 5 - medium-grained granites; 6 - porphyric granites, Precambrian; 7 - Lessovo gneiss-granites; 8 - metaultrabasites; 9 - Zhãlti Chal variegated formation; 10 - Konstantinovo metaconglomerate formation; 11 - Pãnovó porphyroblastic formation; 12 - faults; 13 - a site, suitable for high level RAW disposal (after Kozhoukharov, 1992).

the pluton. The porphyries are of potassium feldspar and are characterized by a great variety of sizes and rock saturations. Their length usually varies from several centimeters to 7-8 cm, sometimes reaching 12-15 cm. The porphyric granites are biotitic to two-mica ones. The uniformly grained granites are medium to coarse grained. They elevate the region between the villages of Glavan, Balgarska Polyana, Hlyabovo, Sakartsi and the neighbourhood of the Bairaka and Karaburun peaks. The micas are of the biotite type, but two-mica varieties also occur.

The mineral composition of the two facial varieties is analogous. They are composed of: quartz, plagioclase, microcline, biotite and occasionally of muscovite and accessory minerals - apatite, zircon, garnet, sphene and clinozoisite. Biotite is often replaced by muscovite and some microclines exhibit later crystallization and active erosion of the plagioclases.

The Alexandrovo leucocratic, apliteoid-pegmatitic granites have a wider distribution than that shown on the map sheet. They occur in the form of elongated bodies

and veins mainly in the east-west direction in the southern parts of the pluton, where they cross the rocks of the Pãnovó and Zhãlti Chal formation and the two facial varieties of the Sakar batholith.

The granites are fine- and medium-grained and occasionally coarse-grained. Three varieties are distinguished among them: medium-grained muscovite granites, coarse-grained pegmatoid granites and fine-grained apliteoid granites. The individual varieties are transformed into each other, but the dominating granites are medium grained, while the apliteoid ones mainly occupy the peripheral parts of the rock bodies or fill some of the veins. These granites do not differ in their mineral composition from the other two varieties of the Sakar batholith except for the biotite content, which is quite rare or missing in the Alexandrovo granites.

Different opinions have formed concerning the age of the Alexandrovo and Sakar granites, covering the range from the Archaic (?) to the Jurassic. The direct geological relationships between the Alexandrovo and Sakar granites, which intrude and contact metamorphose the

rocks of the Paleozoic Klokotnitsa Formation, as well as outliers of granite in the Lower Triassic metasediments (Sakar type) provide the basis for assuming that their age is Upper Paleozoic.

Three categories of terrains are distinguished in the Sakar pluton according to its internal structure. The site, composed of medium-grained granites, indicated by a special symbol on the geological map (Fig. 4.6) is considered to be the most suitable for further investigation and construction of a RAW repository.

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CHAPTER 5

CANADA'S NUCLEAR FUEL WASTE MANAGEMENT PROGRAM: THE ENVIRONMENTAL ASSESSMENT OF THE DISPOSAL CONCEPT

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Abstract. Over the last 17 years under the Nuclear Fuel Waste Management Program, Atomic Energy of Canada Limited (AECL) has developed and assessed a concept to dispose of nuclear fuel waste from Canada's CANDU reactors in a vault excavated in plutonic rock of the Canadian Shield. A robust concept has been developed, with options for the choice of materials and designs for the different engineered components of the disposal system. AECL submitted in 1994 October an Environmental Impact Statement on the Concept for the Disposal of Canada's Nuclear Fuel Waste for review under the Canadian Environmental Assessment and Review Process. If the review is completed in 1996, as currently expected, and if the concept is accepted by the review panel and approved by government, disposal would not likely begin before about 2025.

5.1 INTRODUCTION

About 20% of Canada's electricity is generated using CANDU nuclear reactors. Three provincial utilities, Ontario Hydro, Hydro-Quebec and New Brunswick Power, own these reactors and the used fuel removed from them. The used fuel is currently stored in water-filled pools or in dry-storage concrete storage structures. Current storage practices, while safe, require continuing institutional controls, such as security measures, monitoring and maintenance. Thus, storage is an effective interim measure for the protection of human health and the environment, but not a permanent measure. Disposal is needed to manage nuclear fuel waste in a way that does not depend on institutional controls to maintain safety in the long term.

Canada, like other countries, is basing its plans for disposal of nuclear fuel waste on deep geological disposal in the rock of a continental land mass. The Nuclear Fuel Waste Management Program (NFWMP) was launched in 1978 as a joint initiative by the governments of Canada and Ontario. Under the program, Atomic Energy of Canada Limited (AECL) has been developing and assessing a concept to dispose of nuclear fuel waste in plutonic rock of the Canadian Shield. Ontario Hydro has advanced the technologies for interim storage and transportation of used fuel. The two governments stated in 1981 that selection of a nuclear fuel waste disposal site would not proceed until the concept had been

reviewed and assessed. Thus, a generic rather than a site-specific concept has been developed.

Participants in the program have included AECL, the lead agency for research on nuclear fuel waste disposal; Ontario Hydro, which has advanced the technologies for storage and transportation as well as contributing financially and technically to the R&D on disposal; Natural Resources Canada (NRCan); Environment Canada; scientists at Canadian universities; and consultants in the private sector. An independent Technical Advisory Committee has provided advice on the scope and quality of the technical work.

During the past seventeen years, AECL has carried out detailed studies on the multiple-barrier disposal concept. The objective has been to develop a concept with flexibility in the choice of methods, materials, and designs for the components of the disposal system. The approach has focused on ensuring that the system as a whole meets safety standards by a large margin.

5.2 THE DISPOSAL CONCEPT

The disposal concept being investigated is a proposed method for the geological disposal of nuclear fuel waste in which:

1. The waste form would either be used CANDU fuel or solidified highly radioactive reprocessing waste;

2. The waste form would be sealed in a container designed to last at least 500 years and possibly much longer;
3. The containers of waste would be placed in rooms in a disposal vault or in boreholes drilled from the rooms;
4. The vault would be nominally 500 to 1000 metres deep;
5. The geological medium would be plutonic rock of the Canadian Shield;
6. Each waste container would be surrounded by a buffer;
7. Each room would be sealed with backfill and other vault seals; and
8. All tunnels, shafts and exploration boreholes would ultimately be sealed so that the disposal facility would be passively safe, that is, so that long-term safety would not depend on institutional controls.

After the disposal vault is closed, a series of engineered and natural barriers would protect humans and the natural environment from the radioactive and chemically toxic contaminants in the nuclear fuel waste. These barriers include the waste form; the container; the buffer, backfill and other vault seals; and the geosphere (the rock, any sediments overlying the rock below the water table and the groundwater flow system). Institutional controls would not be required to maintain safety in the long term.

The nuclear fuel waste, or waste form, would be either used CANDU fuel or, if the used fuel was reprocessed in the future, the solidified highly radioactive waste from reprocessing. The low solubility of used CANDU fuel under the expected disposal conditions would make it effective for retaining radioactive and chemically toxic contaminants, thus it is an excellent waste form in its current state. The liquid radioactive waste that would result if used fuel were reprocessed would not be suitable for direct disposal, but such waste could be solidified to produce an excellent waste form.

The waste form would be sealed in a container to facilitate handling and to isolate it from groundwater for a desired minimum time. The container would be designed to have a minimum life of 500 years following emplacement in a disposal vault. As the conditions at potential sites may vary, the container geometry, material and fabrication method would be developed for each particular waste form and site. Important considerations in the design of containers would include the temperature and pressure that would be imposed on the contain-

er at the depth and location selected for the disposal vault and the chemical and microbial environment expected at each site.

The containers of nuclear fuel waste would be emplaced in a disposal vault excavated nominally 500 to 1000 metres below the surface in the plutonic rock of the Canadian Shield. The disposal vault would be a network of horizontal tunnels and disposal rooms that would be excavated deep in the rock, with vertical shafts extending from the surface to the tunnels. Rooms and tunnels might be excavated at more than one level. The vault would be designed to accommodate the rock structure and the subsurface conditions at the chosen site. The method of emplacing the containers in the vault would be selected to suit the specific characteristics of the site and container geometry. Figure 5.1 shows two possibilities for emplacing waste in a vault.

Within the multiple barrier system, the vault seals would perform the following functions to enhance the isolation of the nuclear fuel waste:

1. The buffer would inhibit the movement and modify the chemistry of the groundwater near each container to limit the container corrosion rate, the waste form dissolution rate, and the movement of contaminants;
2. The backfill would fill the space in disposal rooms to keep the buffer and containers securely in place, and in shafts and tunnels to reduce the potential for human intrusion. It would also retard the movement of contaminants by slowing the movement of groundwater, enhancing sorption of contaminants and by chemically conditioning the groundwater;
3. Bulkheads would inhibit groundwater movement at the entrance of disposal rooms, contain any pressures exerted by the backfill, and prevent easy human access to the emplaced waste;
4. Plugs and grouts, located at hydraulically critical locations in the disposal vault, such as locations where shafts and tunnels intersect fracture zones, would inhibit groundwater movement and the potential for contaminant transport in the excavations and in the rock around excavations; and
5. Shaft seals would prevent the shafts from being a preferential pathway for groundwater movement and would reduce the possibility of human intrusion into the sealed disposal vault.

The materials selected for vault seals need to have low hydraulic conductivity (in the order of 10^{-10} m/s or

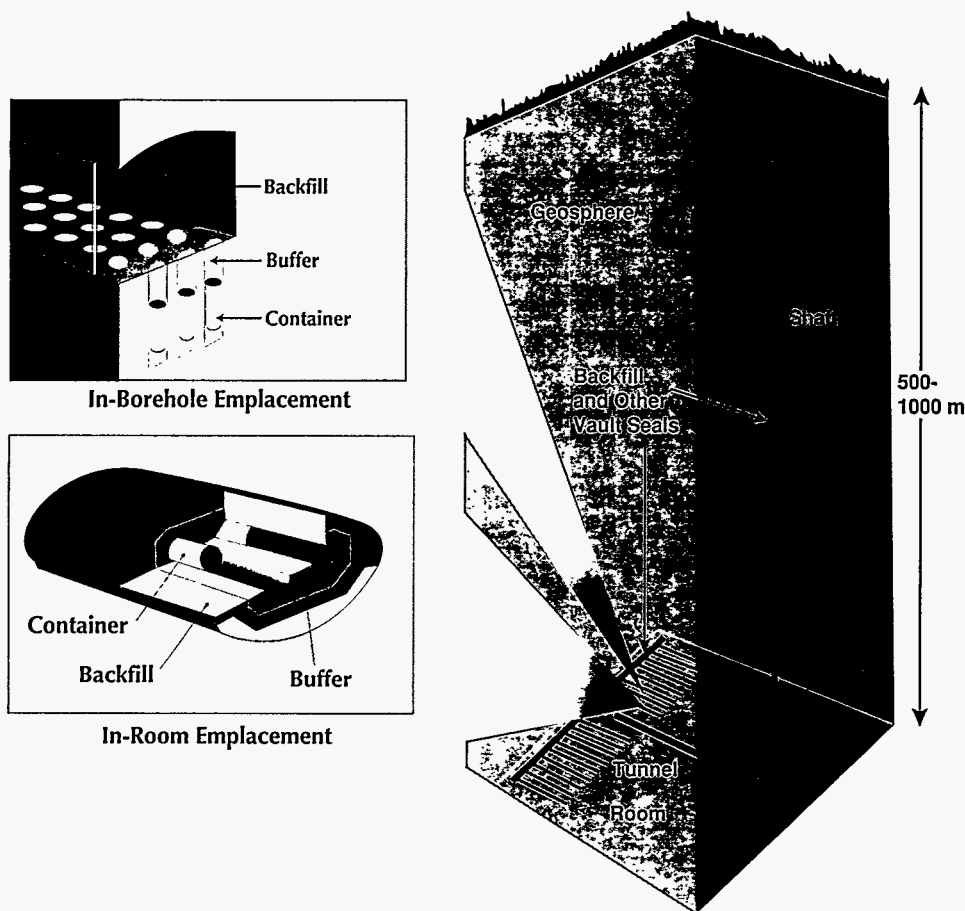


Figure 5.1. The disposal concept showing two examples of waste emplacement.

lower), must be available in the volumes required, must be workable and placeable with current technology, and must have predictable long-term performance.

The geosphere, comprising the plutonic rock, any sediments overlying the rock below the water table, and the groundwater flow system, would surround the disposal vault. The function of the geosphere, as a barrier, would be to protect the waste form, the container and the vault seals from natural disruptions and human intrusion; to maintain conditions in the vault favourable for long-term waste isolation; and to limit the rate at which contaminants from the waste could move from the vault to the biosphere. Any characteristics of a geological medium that support or enhance these functions would be considered favourable.

The plutonic rock bodies of the Canadian Shield are considered favourable as a disposal medium for Canada

because they have many characteristics considered favourable including:

1. Wide geological distribution, allowing flexibility in siting, and wide distribution in regions of low topographic relief, where the driving force for groundwater movement in the rock is likely to be low;
2. Geological stability and the likelihood of remaining stable;
3. Very large size, in many cases, allowing the disposal rooms to be located away from discontinuities;
4. Fewer ore bodies associated with them than other types of rock bodies;
5. Relatively high thermal conductivity to dissipate the heat released from the emplaced waste;
6. Chemical composition and hydrogeological characteristics that favour retention and retardation of the type of contaminants expected in the waste form; and
7. Low frequency of permeable fractures, away from

the widely spaced fracture zones, below a depth of 200 to 500 metres.

The choice of methods, materials, and designs for an actual disposal system will ultimately be made on the basis of performance assessments taking into account the characteristics of the specific site on which the facility is to be developed, availability of materials, cost, and practicality. They could include, for example:

- the form of the waste: used fuel bundles or fuel reprocessing waste incorporated in a stable matrix, e.g. glass or ceramic;
- the disposal container material: titanium alloy, copper, or other durable material;
- the container design;
- the composition of materials used for the buffer, backfill, and other seals;
- the excavation method: blasting or boring;
- the depth, geometry, and the number of levels of the vault;
- the size and shape of the excavated openings; and
- the location of the waste containers: within disposal rooms or in boreholes drilled from the rooms.

These choices will not be made until a site for a vault has been selected.

5.3 ENVIRONMENTAL REVIEW

The federal Department of Energy, Mines and Resources (EMR) (now Natural Resources Canada, NRCan) referred the concept for review under the Environmental Assessment and Review Process (EARP) in 1988. As the "Proponent" for this review, AECL is responsible for preparing and submitting an Environmental Impact Statement (EIS) describing the concept. The Environmental Assessment Panel responsible for carrying out the review is chaired by Mr. Blair Seaborn. The Panel has appointed a Scientific Review Group (SRG), chaired by Professor Raymond Price and composed of eminent scientists from a variety of relevant disciplines, to assist it in judging the technical validity and acceptability of the disposal concept. The Canadian Environmental Assessment Agency (CEAA), formerly Federal Environmental Assessment Review Office (FEARO), provides administrative support to the Panel.

The Panel will review AECL's concept, along with a broad range of nuclear fuel waste management issues. These include the criteria for determining safety and

acceptability; the approaches used in handling nuclear fuel waste both in Canada and other countries; the potential social, economic, and environmental effects of waste disposal; and the potential impact of recycling and other processes on waste volume. A general review of other aspects of the nuclear industry, such as energy policy and reactor operation and safety, is specifically excluded from the Panel's review.

All federal departments with a relevant interest in the concept are expected to participate in the review process. These include the Atomic Energy Control Board (AECB), NRCan, Environment Canada, Health and Welfare Canada, and Transport Canada. NRCan has assembled a team to review the results of AECL's R&D program, and Environment Canada has assembled two teams of experts to review in detail how well the concept protects the environment.

When the EARP review is concluded, the Panel will make recommendations as to the acceptability of the concept and the course of future action regarding nuclear fuel waste disposal. Government decisions will then follow.

In the spring of 1990, CEAA organized a series of "Open Houses" to inform interested parties, not directly connected with the nuclear industry or with the scientific review process, about how they could take part in the review. "Scoping Hearings" took place in the autumn of 1990 to identify issues of concern, and to assist the Panel in setting guidelines for the EIS. One hundred and thirty participants made presentations, including government departments, scientific and business organizations, special interest groups, and private individuals. Among the major issues raised were arguments for and against storage as compared with disposal, the adequacy of the regulatory criteria, and monitoring the performance of the disposal vault. Aboriginal land claims affect much of the land where a disposal vault could be sited. In view of this, an aboriginal representative was added to the Panel.

In June 1991 the Panel issued draft Environmental Impact Statement guidelines for comment. Over thirty different groups and individuals submitted comments. The Panel issued its final guidelines to AECL in March of 1992.

AECL responded to these guidelines by preparing and issuing the Environmental Impact Statement and nine primary reference documents to support the

Environmental Impact Statement. These documents provide a complete description of the concept and the technology that has been developed over the past 15 years. The EIS also provides additional information specifically requested by the Panel.

The nine primary references were issued in 1993 and 1994. The Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste, and the Summary of the Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste were completed and submitted to the EARP Panel in 1994 October. The Panel released these documents to the public and initiated a nine month review period for the public to assess their completeness and provide comments to the Panel. By 1995 January 31, AECL had distributed about 18,500 copies of these documents.

From 1994 November to 1995 March, CEAA conducted another series of Open Houses in 21 communities across the review provinces; New Brunswick, Quebec, Ontario, Manitoba and Saskatchewan. These were designed to familiarize the public with the review process, the disposal concept, and nuclear fuel waste transportation and storage and to encourage their participation in the review of the completeness of the EIS and in the Public Hearings announced for later. At many of the Open Houses, short formal presentations were made by CEAA, AECL and Ontario Hydro staff. These were often followed by a question period. About 2750 people attended the presentations or visited the AECL exhibit.

The environmental assessment panel released its approach for the public hearings in 1994 August. The approach is divided into three phases:

1. Phase I is designed to assist the panel addressing issues in the panel's terms of reference which go beyond the generic concept for deep geologic disposal including: the criteria by which safety and acceptability of a concept for long-term management and disposal should be evaluated; the degree to which this generation should relieve future generations of the burden of caring for the waste; social, economic and environmental implications of a possible nuclear fuel waste management facility; the general criteria for site selection and a future site selection process; and the potential costs and benefits to potential host communities. This phase is scheduled for 1996 March and April in Toronto and other communities in Ontario.

2. Phase II of hearings will focus specifically on scientific and technical issues related to the safety of the AECL's generic concept for deep geologic disposal of nuclear fuel waste. This phase is scheduled for 1996 June in Toronto.
3. Phase III hearings will be held over six weeks in the autumn of 1996 in a number of communities in five provinces previously visited by the panel during the scoping phase of this review. This phase will involve presentations on: recommendations to assist governments in reaching decisions on the acceptability of the disposal concept; steps to be taken to ensure safe long-term management of nuclear fuel waste; criteria by which the safety and acceptability of a concept for long-term waste management and disposal should be evaluated; social, economic and environmental implications of a possible nuclear fuel waste management facility, including the impact of transportation of nuclear fuel waste; general criteria for site selection and on a future site selection process; and the costs and benefits to potential host communities.

5.4 THE ENVIRONMENTAL IMPACT STATEMENT AND PRIMARY REFERENCES

The Environmental Impact Statement document provides an overview of AECL's case for the acceptability of the disposal concept, and provides information about the following topics:

- the characteristics of nuclear fuel waste;
- storage and the rationale for disposal;
- major issues in nuclear fuel waste management;
- the disposal concept and implementation activities;
- alternatives to the disposal concept;
- methods and results of the environmental assessments;
- principles and potential measures for managing environmental effects; and
- AECL's overall evaluation of the disposal concept.

The nine Primary References expand on particular socioeconomic and technical aspects AECL has evaluated in developing the concept:

Public Involvement and Social Aspects

- describes the activities undertaken to provide information to the public about the program and to obtain public input into the development of the disposal

- concept;
- presents the issues raised by the public and how the issues have been addressed during the development of the disposal concept or how they could be addressed during the implementation of the disposal concept; and
- discusses social aspects of public perspectives on risk, ethical issues associated with nuclear fuel waste management, and principles for the development of a publicly acceptable site selection process.

Site Screening and Site Evaluation Technology

- discusses geoscience, environmental, and engineering factors that would need to be considered during a siting process; and
- describes the methodology for site characterization, that is, for obtaining the data about regions, areas, and sites that would be needed for facility design, monitoring, and environmental assessment.

Engineered Barriers Alternatives

- describes the characteristics of nuclear fuel waste;
- describes the materials that were evaluated for use in engineered barriers, such as containers and vault seals;
- describes potential designs for containers and vault seals; and
- describes procedures and processes that could be used in the production of containers and the emplacement of vault-sealing material.

Engineering for a Disposal Facility

- discusses alternative vault designs and general considerations for engineering a nuclear fuel waste disposal facility;
- describes a reference disposal facility design that was used to assess the technical feasibility, costs, and potential effects of disposal (The term "reference" is used to designate the disposal systems, including the facility designs, specified for the assessment studies. Different disposal facility designs are possible and might be favoured during concept implementation.); and
- presents cost and labour estimates for implementing the reference design.

Preclosure Assessment of a Conceptual System

- describes a methodology for estimating effects on human health, the natural environment, and the

socioeconomic environment that could be associated with siting, constructing, operating (including transporting used fuel), decommissioning, and closing a disposal facility;

- describes an application of this assessment methodology to a reference disposal system;
- discusses technical and social factors that would need to be considered during siting; and
- discusses possible measures and approaches for managing environmental effects.

Postclosure Assessment of a Reference System

- describes a methodology for:
 - estimating the long-term effects of a disposal facility on human health and the natural environment,
 - determining how sensitive the estimated effects are to variations in site characteristics, design parameters, and other factors, and
 - evaluating design constraints; and
- describes an application of this assessment methodology to a reference disposal system.

The Vault Model for Postclosure Assessment

- describes the assumptions, data, and models used in the postclosure assessment to analyze processes within and near the buried containers of waste; and
- discusses the reliability of the data and models.

The Geosphere Model for Postclosure Assessment

- describes the assumptions, data, and models used in the postclosure assessment to analyze processes within the rock in which a disposal vault is excavated; and
- discusses the reliability of the data and models.

The Biosphere Model, BIOTRAC, for Postclosure Assessment

- describes the assumptions, data, and models used in the postclosure assessment to analyze processes in the near-surface and surface environment; and
- discusses the reliability of the data and models.

The EIS and the nine Primary References comprise some 6000 pages.

5.5 REASONS FOR CONFIDENCE IN THE DISPOSAL CONCEPT

Our confidence in the long-term safety of the concept

draws strength from a number of sources:

1. The technical approach, the use of multiple barriers for redundancy and defence in depth;
2. The adoption of an observational approach to site characterization and to disposal vault design, construction, operation and eventually closure;
3. An approach to the project which is based on ongoing review and decision-making and which recognizes that, throughout, the process must be flexible and responsive and that decisions can be modified; and
4. Active and effective involvement of the public in the process.

5.6 THE MULTIBARRIER SYSTEM

In common with the approach adopted in other countries, the concept developed by AECL involves isolating the waste from the biosphere by a series of engineered and natural barriers. AECL's approach to development of the disposal concept has been to consider the performance of the system as a whole, rather than focusing on performance requirements for individual components. This approach allows flexibility in implementation to be retained and it increases the likelihood of identifying any counterintuitive interactions or synergisms among system components that could adversely affect safety. Thus, the performance of individual components, such as waste containers, is analyzed in the context of the system. This contrasts with a design and safety approach that prescribes performance standards for individual components and evaluates safety by the analysis of the performance of each component independently. Our goal, therefore, has been to develop a thorough scientific understanding of the performance of the different components of a disposal system and how these components interact and influence one another, so that the overall system can be designed to provide defence in depth.

Acquiring and building the necessary knowledge base is a continuing process, and in implementing disposal, flexibility must be retained so that new information and understanding acquired over time can be integrated into the disposal system. An example is container life-time. The original target was to achieve a minimum container life-time of 500 years and early work established that this goal could be achieved with a thin-walled titanium container. Subsequent studies on the corrosion of titanium and copper indicated that, for the expected groundwater chemistry, thin-walled titanium containers can be designed to have a corrosion lifetime in excess of tens of

thousands of years, and a 25 mm thick copper container can potentially provide containment in excess of 10^6 years. Such advances in understanding and in our ability to defend, scientifically, this understanding can have a profound impact on the approach taken to facility design and implementation, and on decision-making.

Much of the evidence needed to evaluate any site that would be considered for deep geological disposal can be obtained from geologic information developed as the site is characterized, i.e., from the record of past changes preserved in the native rock mass and the groundwater. In the Canadian Shield the record available for investigation can be as long as two billion years.

Investigations at our field research areas, for example, indicate that discrete zones of intensely fractured rock, intersecting otherwise sparsely fractured rock, are the dominant pathways for groundwater flow at depths greater than 300 m to 500 m in plutonic rock of the Canadian Shield. The flux of groundwater can be high in the fracture zones; however, the flux is very low in the sparsely fractured rock bounded by the fracture zones, due to its very low permeability, which is commonly less than 10^{-18} m². Such low permeabilities can limit the rate of contaminant movement and indicate that within the overall disposal system, the host rock can play an important role as a natural barrier to the transport of radionuclides.

The field evidence is supplemented and complemented by understanding derived from laboratory studies. Field studies, including studies of natural analogues, can extend the short-term evidence from the laboratory studies to the longer times of interest - tens and even hundreds of thousands of years - and provide verification of the understanding incorporated in predictive modeling. For example, studies of the Cigar Lake uranium deposit in northern Saskatchewan have been under way since 1984. The uranium ore in the deposit has essentially the same composition as used fuel. It was formed some 1.3 billion years ago and has been in contact with groundwater since its deposition. Yet the uranium has remained stable under the reducing conditions prevailing in the deposit. Similar conditions are expected to occur in a disposal vault.

5.7 THE OBSERVATIONAL METHOD

No organization in Canada has yet been given the mandate to proceed with siting a disposal facility. Nevertheless, we can anticipate that the approach that will be used in site characterization and disposal vault

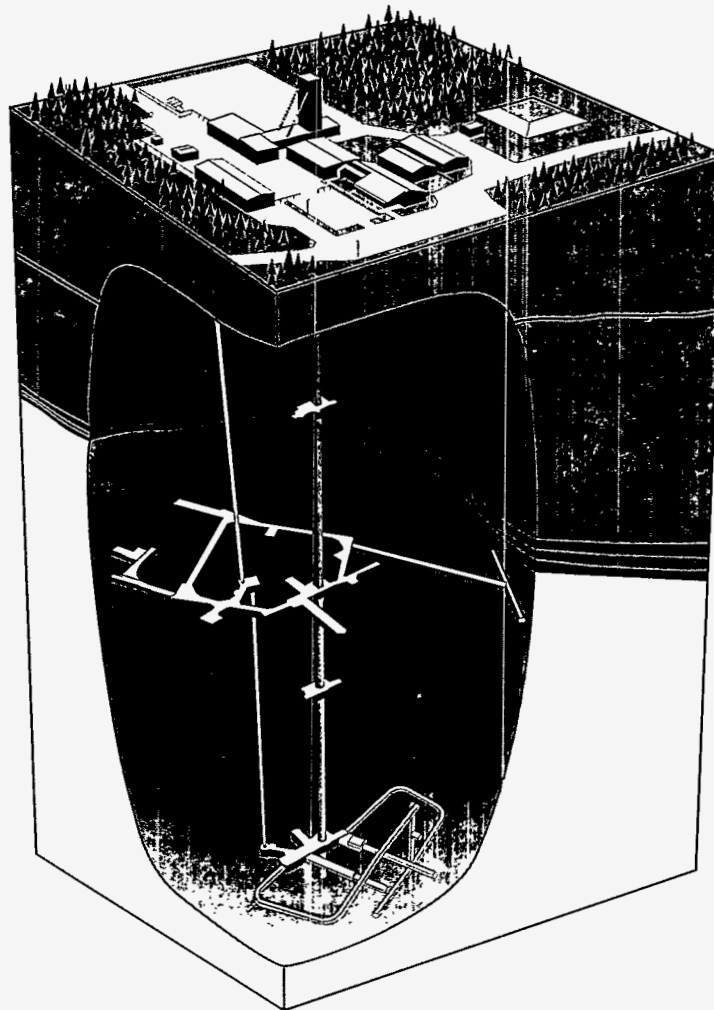


Figure 5.2. Underground research laboratory.

design, construction, operation, and eventually closure will be based on the observational method - the approach used in good geotechnical engineering. The observational method is a systematized approach to dealing with practical problems encountered when engineering in the sub-surface. In this approach, the results of modeling and computations during design are viewed as working hypotheses subject to confirmation or modification during construction. This approach provides a framework for decision-making in a situation where it is not practical, even if it were possible, to obtain all the detailed geotechnical information that would be needed for design of an underground facility prior to excavation at the site. As the project proceeds, the information is continuously acquired and incorporated into the design. A lack of detailed knowledge about local variability within a selected rock mass prior to excavation is common in underground construction. Nevertheless, major projects such as underground powerhouses and storage

chambers, transportation tunnels, and dams are completed successfully using a design approach that accommodates observations made as construction is advanced. As part of its research program, AECL has constructed an Underground Research Laboratory for large-scale testing and *in-situ* engineering experiments on aspects of disposal (Figure 5.2). The observational method was used during the design and construction of this facility.

The observational method is also central to the use of performance assessment analyses as part of the design and implementation process. It is a continuously applied, iterative process. Beginning during the site selection phase, assessments are made based on all available data on the site conditions. The understanding of the site is incorporated into models for use in design and in performance assessment studies. Both the designs and the assessments become more refined as the knowledge of a site increases. Design and operational deci-

sions are made on the basis of the understanding of site conditions at the time. The maximum possible flexibility is retained to incorporate technological improvements. In addition, the potential impacts of conceivable deviations from site conditions as understood need to be assessed and contingency measures established, in advance, to address the deviations should they be encountered.

As work proceeds, observation and evaluation of the actual conditions encountered are compared with the previous understanding and, if necessary, the detailed design and the models used in performance assessment are modified. This cycle continues throughout site selection, construction and operation, so that at each point when significant licensing and operational decisions need to be made, a long record of observation and a series of increasingly refined performance assessments are available on which to base the decision.

5.8 ONGOING REVIEW AND DECISION-MAKING

AECL views the current review as the beginning of a continuing process. As the technology for managing the disposal of nuclear fuel waste is developed and applied to specific sites, further reviews and public consultation and involvement will be needed. Any facility will be subject to rigorous regulatory criteria, and it is anticipated that society will demand that a step-by-step process be followed. Thus, a decision to proceed on the basis of the current review would represent only the first of a series of decisions between distinct phases of the process.

Each phase should lead to increased confidence in the overall system, thus facilitating decision-making about how and whether to proceed to the next phase. We are currently nearing the end of the first phase - concept development and assessment. If the Panel shares AECL's view that we have adequately developed the concept, and there is a governmental decision to proceed, the next appropriate step would be the start of site-specific activities, beginning with site screening. The sequence of events could be as follows:

1. Site screening would lead to the selection of one or more sites for detailed characterization based on surface techniques;
2. Such site characterization studies could lead to a selection of one or more sites for exploratory excavation and more extensive in-ground characterization;
3. In-ground characterization could lead to a decision to initiate construction and operation of a disposal

vault, possibly beginning with a demonstration phase;

4. Design, construction and operation of a facility would involve ongoing review, reassessment and recommitment, leading to continued operation and then eventually to a decision to cease operations and decommission; and
5. Decommissioning and post-operational monitoring would ultimately lead to a decision to close and seal the vault.

The process of site screening and of evaluating several sites will likely involve a further ten to fifteen years of work before a commitment would be made to initiate an underground excavation, followed by a further ten years or so of site exploration and characterization before construction could begin. Thus, waste would not be emplaced in a vault before about 2025. By then we would have accumulated many years of site-specific data and a series of increasingly refined evaluations on which to base a decision to begin to emplace waste.

The decision to close and seal the vault would be made on the basis of the accumulated evidence and experience gained throughout the siting, characterization and operational phases, a process extending over close to a century. Only with that decision will disposal based on the concept have definitively been judged as safe and acceptable.

Thus, at the current concept assessment phase of the process, "concept approval" represents a judgment that:

- sufficient understanding has been developed to continue with the process, with an expectation that we will eventually reach the end point of sealing a vault; and that
- at the appropriate time, we should proceed to the next phase of the program, the beginning of site-specific activities to resolve outstanding issues that can only be resolved on a site-specific basis.

5.9 PUBLIC INVOLVEMENT

The general public and potential host communities are important constituencies which contribute to the decision-making when identifying options for waste management. Building public confidence in a program is therefore an important part of its development. The process to be followed in reviewing the program and deciding on future steps should involve consultation with, and the active participation of, the communities and public affected. Decision-makers need to have a

mechanism to take public concerns into account when advancing major projects such as a disposal facility.

In Canada a formal mechanism for public involvement in the early part of project development is defined in environmental assessment and review legislation. The objective is to establish the scope of public concerns and interest early in the planning stage of a project so that steps can be taken to address the concerns in the project design. The public is asked to formally participate in the assessment and review and may be provided with the funds to do so.

In the Canadian program, no site will be selected for a disposal facility until the technology has first been evaluated in an environmental review. This review is currently under way. Because no directly affected community exists, public involvement at this stage is necessarily very broadly based. As part of concept development, AECL has carried out a public interaction program with the objectives of providing information to the general public and to those groups which have shown a particular interest in the program. At the same time we have endeavoured to identify the issues of concern to the public and to address these in the documentation describing the technology and our approach to disposal.

If the environmental review leads to a decision to proceed toward selecting a site, we anticipate that public involvement will continue and that it will become more community-specific. Beginning with siting, the organization selected to implement disposal, the implementing organization, would need to develop and maintain effective working relationships with potential host communities and with communities along potential transportation corridors. For these relationships to be effective, the implementing agency must demonstrate a commitment to principles of fairness, openness, shared decision-making, and above all to safety, so that affected communities can participate fully in the decision-making and so become empowered.

AECL proposes that the implementing organization adhere to the following principles:

Safety and Environmental Protection

In addition to complying with all applicable legislation, the implementing organization would keep adverse effects on human health, the natural environment, and the socioeconomic environment as low as reasonably achievable, taking social and economic factors into

account.

Voluntarism

No community would be forced to host a disposal facility. A community would have the right to determine whether or not it was willing to be a host community.

Shared Decision Making

Implementation of the concept would occur in stages and would entail a series of decisions about whether and how to proceed. Each potential host community, and eventually the host community, would share in the decision making. In addition, the implementing organization would seek and address the views of other potentially effected communities.

Openness

Throughout the project, the implementing organization would offer information to the general public about its plans, procedures, activities, and progress. In addition, potentially affected communities would have access to all available information required to make a judgment about safety and environmental protection.

Fairness

In accepting a disposal facility, the host community would provide a significant service to the consumers of nuclear-generated electricity and to the public at large. In fairness, the net benefit to the host community should be correspondingly significant. The net benefit is not intended to induce a community to accept an unsafe disposal facility. As part of the negotiated program for managing environmental effects, measures would be taken to avoid, mitigate, or compensate for adverse effects; such measures would be enhanced or additional measures taken to ensure the betterment of the host community. Fairness also requires "due process," which would be provided by adherence to the principles of voluntarism, shared decision making, and openness.

The principle of safety and environmental protection would not be compromised, no matter how acceptable or desirable a site might be in all other respects.

5.10 CONCLUSIONS AND RECOMMENDATIONS

AECL believes that it has developed a robust and flexible concept for disposal of nuclear fuel waste that will

meet the regulatory requirements of Canada. In our EIS we conclude that:

1. Implementation of the disposal concept would protect human health and the natural environment from the potential adverse effects of nuclear fuel waste far into the future. In addition, human health and the natural environment would be protected while the disposal concept was being implemented.
2. The disposal concept provides a means of minimizing the burden on future generations.
3. The disposal concept provides scope for public involvement during implementation.
4. Of the options that have been considered internationally, only geological disposal is a viable alternative for the disposal of Canada's nuclear fuel waste using currently available or readily achievable technology. The choice of plutonic rock of the Canadian Shield as the preferred disposal medium, made in the late 1970s, was appropriate, and plutonic rock should remain the preferred disposal medium for Canada.
5. The disposal technology does not rely on institutional controls as a necessary safety feature; it is adaptable to a wide range of physical conditions and to potential changes in criteria, guidelines and standards, and it includes monitoring and retrievability.
6. The methodology to evaluate safety of a disposal system against established safety criteria, guidelines, and standards has been developed and demonstrated to the extent reasonably achievable in a generic research program.
7. Technically suitable sites are likely to exist in Canada.

We are confident that implementation of our disposal concept represents a means by which Canada can safely disposal of its nuclear fuel waste.

We are continuing research and development work to ensure the public and the industry have as much confidence as possible in the safety of the concept and in the feasibility of implementing it.

The process for a federal environmental review of the concept is well under way. The review of a concept as opposed to a site- and design-specific project requires focusing on whether it is appropriate to proceed with the first phase of implementation. We believe that we have reached the stage in the NFWMP where the greatest benefit will result if activities proceed on a site-specific basis. Therefore, we have made the following recommendations in the EIS:

1. We recommend that the strategy for long-term management of Canada's nuclear fuel waste be based on the concept of disposal in plutonic rock of the Canadian Shield.
2. We recommend that those who have responsibility for the safe management of used fuel - the federal government and owners of the used fuel - also have responsibility for implementing the concept. In addition to addressing their requirements, the plan for implementation should address the requirements of any provincial government that could be affected by implementation, and those resulting from the present environmental review.
3. We recommend that those responsible for implementing the disposal concept be committed to the principles of safety and environmental protection, voluntarism, shared decision making, openness, and fairness.
4. We recommend that Canada progress toward disposal of its nuclear fuel waste by undertaking the first stage of concept implementation - siting.

We are in a very public process. Our experience has shown us that such processes are not easy for the nuclear industry. We believe that the information included in the EIS should lead the Panel to recommend that we proceed to the next phase of the process leading toward disposal. Our confidence is founded on the strength and depth of our technical program and on a well-founded public consultation program.

CHAPTER 6

DEEP GEOLOGICAL DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE IN CHINA

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6.1 INTRODUCTION

China is now facing the challenge of how to safely dispose of nuclear waste. China's nuclear industry was first established in 1955, five years after the birth of the People's Republic of China. With the development of nuclear facilities, more and more radioactive waste has been generated. Much of liquid high level waste has been accumulated to date (Luo et al, 1995), and it is stored in stainless steel casks, waiting for vitrification.

On the Chinese mainland, there are two nuclear power

plants (NPPs) in operation: the Qinshan NPP in east China's Zhejiang province and the Daya Bay NPP in south China's Guangdong province (Fig. 6.1). In the next five years, four more NPPs (8 units) will be built (Fig. 6.1); their estimated capacities are listed in Table 6.1. China has plans for a significant nuclear energy development. The total electrical capacity produced by the NPPs is planned to reach 20,000 MW by 2010. In the near future, China is also facing the problem of disposing of the spent nuclear fuel from the NPPs. At present, the national policy is that the spent fuel should be reprocessed before final disposal.



Figure 6.1. Map showing distribution of nuclear power plants (NPPs) on Chinese mainland. Legend: A - Daya Bay NPP; B - Lin'ao NPP; C - Qinshan NPPs (Phases 1, 2, and 3); and D - Liaoning NPP. Preselected regions for development of HLW repository: 1 - southwest China (granite, shale); 2 - Guangdong area (granite); 3 - Inner Mongolia (granite); 4 - east China (granite, tuff); and 5 - northwest China (mudstone, shale, granite).

Table 6.1. Nuclear power plants of China.

	Name of NPP	Province	Capacity (MW)	Remarks
1	Qinshan	Zhejiang	300 x 2	in operation
2	Qinshan (2nd phase)	Zhejiang	600 x 2	under construction
3	Qinshan (3rd phase)	Zhejiang	700 x 2	to be built
4	Daya Bay	Guangdong	900 x 2	in operation
5	Lin'ao	Guangdong	1,000 x 2	under construction
6	Liaoning	Liaoning	1,000 x 2	to be built

6.2 ORGANIZATION

In China, work related to radioactive waste disposal is managed by the China National Nuclear Corporation (CNNC). The organizational structure for the disposal of high level radioactive waste is shown in Figure 6.2.

The China Environmental Protection Agency is responsible for the issuance of related regulations, the final review of environmental impact statements, and the licensing for the construction and operation of a repository. The China National Nuclear Safety Administration is responsible for the safety issues related to the dispos-

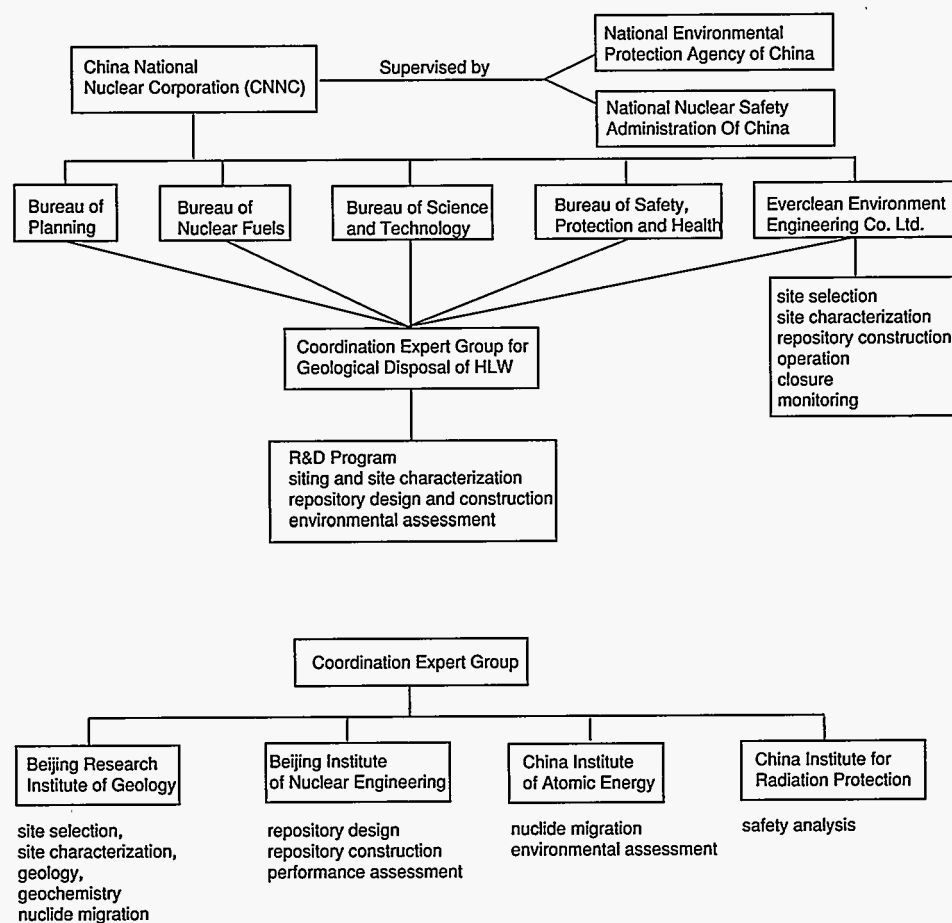


Figure 6.2. China's organizational structure for the disposal of high level radioactive waste.

al of high level waste.

The CNNC is responsible for the transportation of HLW and spent fuels, reprocessing of spent fuels, vitrification of liquid HLW, and final geological disposal of HLW. Under CNNC, four bureaus are involved in the disposal process: Bureau of Planning, Bureau of Nuclear Fuels, Bureau of Science and Technology and Bureau of Safety, Protection and Health.

The Everclean Environment Engineering Corporation, attached to CNNC, is responsible for site selection, site characterisation, construction, operation, closure and monitoring of repositories of low and intermediate level, and high level radioactive waste.

A Coordination Expert Group was organized for the geological disposal of HLW in 1986. The group is composed of experts from the Beijing Research Institute of Geology, Beijing Institute of Nuclear Engineering China Institute of Atomic Energy, and China Institute for Radiation Protection. The group is responsible for R & D programs, site selection, research work related to site characterization, repository design, environmental assessment, safety analysis and performance assessment.

6.3 DEEP GEOLOGICAL DISPOSAL PROGRAM

In 1985, CNNC worked out an R & D program which has been called the Deep Geological Disposal (DGD) of HLW (Yang, 1992). The program is divided into 4 phases:

Phase 1: 1985-2025 Site Selection and Site Characterization

1. 1985-1986, Nationwide screening;
2. 1986-1988, Regional screening;
3. 1989-2010, District screening and preliminary site characterization;
4. 2011-2015, Pre-feasibility study of the pre-selected district;
5. 2015-2017, Licensing for site characterization;
6. 2017-2023, Site characterization and suitability study; and
7. 2023-2025, Licensing for the site.

Phase 2: 2025 - 2029, Repository Design

Phase 3: 2041-2050, Repository Construction

Phase 4: 2051- , Repository Operation.

Between Phase 2 and Phase 3, there is a 10-Year interval, during which an underground research laboratory will be built near the selected site between 2028 and 2033. A full-scale *insitu* test and disposal demonstration will be conducted in the laboratory between 2034 and 2040. The final repository design will be revised after the work in the underground research laboratory is finished.

According to China's policy, the final form of the disposed waste will be vitrified radiowastes after reprocessing. The conceptual design for the HLW repository will be a shaft-tunnel model, which will be located in the saturated zone in granite.

6.4 PROGRESS IN SITE SELECTION

According to the DGD Program, the site selection for China's HLW repository is in progress, and granite is considered as the candidate host rock for the repository. The site selection process, started in 1985, is composed of 4 stages: nationwide screening, regional screening, district screening and site screening. At present, the third stage has been reached, and the screening efforts are focused on the Beishan area, Gansu province in northwest China.

6.4.1 Siting Criteria

Because of the high radiotoxicity and long half-life of radionuclides in high level waste, sites for HLW repositories should be selected very carefully. Siting guidelines, or siting criteria, have been issued by many countries or international organizations, such as USA, Sweden, EC, IAEA, etc. Taking China's situation into account, as well as experience in other countries, we proposed preliminary siting guidelines that have been followed during our work (Xu, 1992).

The general siting principle is that, under the effects of natural and human activities, the long term (100,000 year) safety of the repository can be obtained, and the disposed radioactive wastes can be prevented from entering the biosphere and harming human beings. Furthermore, the following factors are considered in the siting process. However, detailed and exact technical requirements and limits for these natural factors have not been worked out.

Social Factors

- the distribution of nuclear industry in China;
- the animal and plant resources, the potential mineral

- resources;
- the attitude of the public and the local government;
- the requirement of national environmental protection laws; and
- the feasibility for construction and operation of the repository.

Natural Factors

- natural geography, including topography, climate, hydrology etc.;
- geology, including crustal stability (earthquakes, active faults, etc.); and
- crustal stress, crustal thermal flow, host rock type, hydrogeology and engineering geology.

6.4.2 Progress in Site Selection

Since 1985, the site selection for China's HLW repository has progressed through three stages: (1) nationwide screening (1985-1986); (2) regional screening (1986-1988); and (3) district screening (1989-present).

Nationwide Screening (1985-1986)

During this stage, the first work was the investigation of the site selection process conducted in other countries. Then, based on these experiences, and considering the distribution of China's nuclear industry, the problems of crustal stability and social economic conditions, the following five regions were selected for the repository (Fig. 6.1): southwest China, Guangdong Area, Inner Mongolia, east China, and northwest China. In this stage, granite, tuff, mudstone and shale were considered as candidate host rocks.

Regional Screening (1986-1988)

Based on the work of Stage 1, twenty-one districts were selected for further investigation within the five above mentioned areas:

- Southwest China.* Three districts were selected: Hanwangshan district, Zhongba district, and Hannan district. The potential host rocks are shale, biotite granite, and plagioclase granite, respectively.
- Guangdong Area.* Since the Daya Bay NPP is located in this area and more NPPs are planned to be built, it was considered a potential area for the HLW repository. The candidate geological formations are the Fuogang granite body and the Jiufeng granite body. However, because of the rapid development in the

Guanadong province, this area may not be considered for further investigation.

- Inner Mongolia.* The selected districts, including Parjiang Haizhi and Dabaolitu districts, are located in central Inner Mongolia. The host rock is Hercynian granite.
- East China.* In east China's Zhejiang and Anhui provinces, six districts have been selected: Lin'an, Gaoyu, Chenshi, Jiangshan, Guangde and Yixian. The host rocks include granite and tuff. The Chenshi district is located on a small island composed of granite.
- Northwest China.* The selected area is located in northwest China's Gansu Province. It is the most promising area for the construction of a HLW repository. It is an arid gobi area with very low population density and without an economic potential. A total of five districts have been selected for investigation:

- Toudaohe-Xitianjinwei, biotite monzonitic granite;
- Kuangqu, mudstone;
- Baiyuantoushan, quartz diorite;
- Qianhongquan, K-feldspar granite and plagioclase granite; and
- Jiujin, plagioclase granite.

District Screening (1989-present)

Since 1989, our work has been focused on northwest China, with granite considered as the candidate host rock. The following aspects of the area have been studied: earthquakes, structural framework, active faults, crustal stability, lithology, hydrogeology, and engineering geology. According to the crustal stability, we consider the Qianhongquan and Jiujin districts, located in the southern part of the Beishan Folded Belt, as the most promising districts, and further work will be conducted in those areas.

6.5 BEISHAN AREA, GANSU PROVINCE, NORTHWEST CHINA

6.5.1 Regional Geology

Regional Tectonics

The Beishan area in Gansu Province, is the preselected area for a HLW repository in China. Geographically, the Beishan area is located north of the town of Yumen in northwest Gansu province, China. Tectonically, it is located in the Erdaojin-Hongqishan compound anticline

of the Tianshan-Beishan folded belt (Fig. 6.3). The anticline strikes nearly east-west, with its core composed of schist, laminated migmatite of the Laojunmiao Group and Dakouzhi Group of pre-Changchengian age, and its limbs are composed of schist, marble, quartzite and migmatite of the Yujishan and Huayaoshan Groups of pre-Changchengian age. In addition, along the limbs, there are Jiujin Caledonian magmatite (plagioclase granite), Baiyuantoushan Caledonian magmatite (quartz

diorite) and Qianhongquan Hercynian magmatite (monzonitic and orthoclase granites). These magmatite rocks are the main candidate host rocks for the repository.

The border between the Beishan area and the Hexi Corridor Transitional zone is the blind Sulehe fault. Within the Beishan area there are three east-west-striking large scale ductile shear zones (DSZ), namely: South Erduanjin, Zhongqiujiu-Jinmiaogou, and Erdojin-

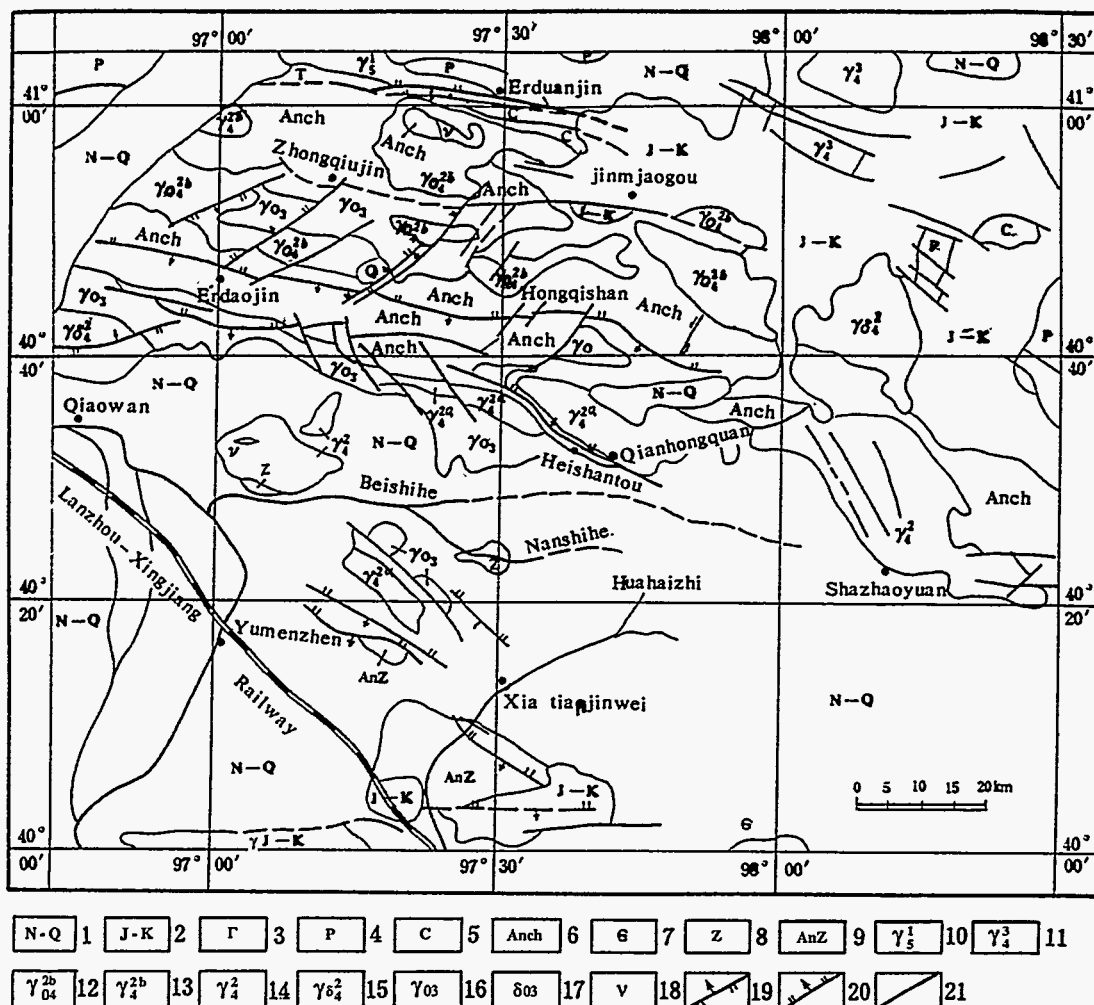


Figure 6.3. Geological sketch map of the Beishan area, Gansu Province, northwest China containing the pre-selected area for China's high level radioactive waste repository. Legend: 1 - Tertiary and Quaternary sediment; 2 - Cretaceous and Jurassic sandstone, shale and sandstone; 3 - Triassic conglomerate and pebbly sandstone; 4 - Permian System; 5 - Carboniferous system; 6 - Pre-Changchengian schist, gneiss, marble and migmatite; 7 - Cambrian System; 8 - Sinian System; 9 - Pre-Sinian System; 10 - Yanshanian granite; 11 - Hercynian granite; 12 - Hercynian plagioclase granite; 13 - Hercynian orthoclase granite; 14 - Hercynian Plagioclase granite and two-mica granite; 15 - Hercynian granite diorite; 16 - Caledonian plagioclase granite; 17 - Caledonian quartz diorite; 18 - gabbro vein; 19 - normal fault; 20 - reverse fault; and 21 - fault.

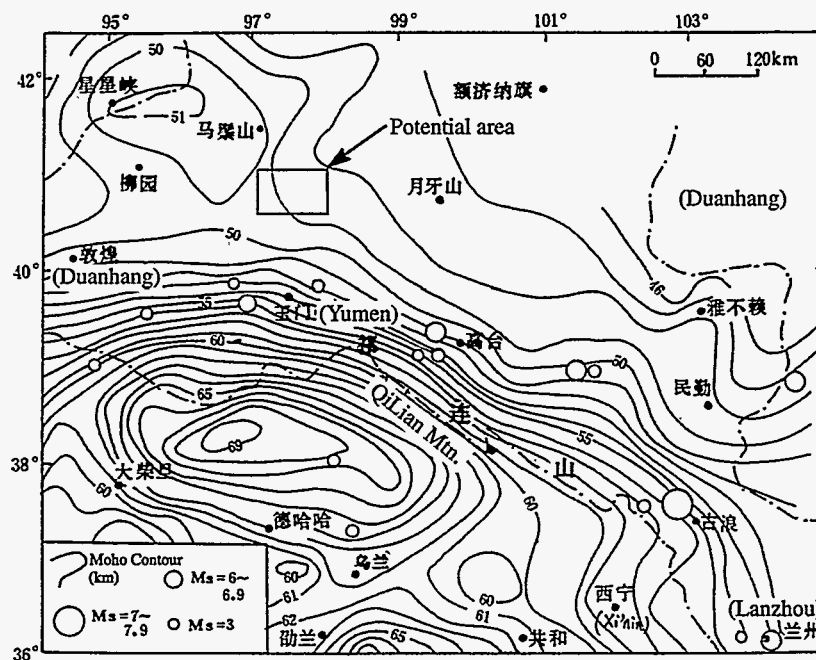


Figure 6.4. Moho discontinuity iso-depth contour map of northwest Gansu, China.

Hongqishan. The activity of brittle faults developed within the shear zones is a key factor affecting the crustal stability of the area.

The Zhongqiujiu-Jinmiaogou DSZ is east-west striking with a length of 90 km and a width ranging between 50 and 2000 m. It was developed in monolithic gneiss, granite and sericite slate during the Hercynian period. The maximum depth of the shear zone is about 10 km. Several east-west striking brittle faults are developed in the shear zone. However, these faults do not cut the Quaternary sediments, and no earthquakes with $M_s > 4^{3/4}$ have been recorded along them, which indicates that they are not active faults.

The Erdaojin-Hongqishan DSZ is about 130 km long and has a maximum width of 7 km. The southern and northern borders of the shear zone are two east-west striking brittle faults which are not active faults, either.

Crustal Structure

According to the main tectonic units, deep geophysical features and the crustal thickness, the crustal structure of the western Gansu province can be divided into the areas of Beishan-Alashan, North Qilian Mt., Hexi corridor, and Qilian. The selected area for the HLW repository is located within the Beishan-Alashan area. The depth contour of the crust in the area strikes NWW-EW.

The thickness of the crust is 47-50 km (Fig. 6.4), and it gradually increases from north to south with very little variation. The gravity anomaly is -150 to $-225 \times 10^{-5} \text{ m/s}^2$ (Fig. 6.5) with a gradient that is less than 0.6 mGal/km . On the gravity anomaly map, the contours are very sparse without obvious step zones, indicating that there are no large faults extending to the depth of the crust. Based on these characteristics, the crust in the Beishan area possesses a block structure with good integrity.

Earthquake Activity

Earthquakes are a demonstration of modern crustal movement, and have a close relationship with tectonic movement, especially with the intensive activity of large deep-rooted faults. The Beishan area is located north of the Hexi Corridor earthquake zone. In this area, there is a lack of large active deep-rooted faults and strong earthquakes. According to data provided by the National Seismological Bureau of China, no earthquakes with $M_s > 4^{3/4}$ have been recorded in the Beishan area. On the "Seismic Intensity Regionalization Map of China (1:4,000,000)", the Beishan area is within a VI seismic intensity region (Fig. 6.6).

In sharp contrast to the Beishan area, the Hexi Corridor earthquake zone has several active NWW deep-rooted faults. Along the North Hexi Corridor Great Fault, several intensive earthquakes took place, e.g., the $M=7 \frac{1}{4}$

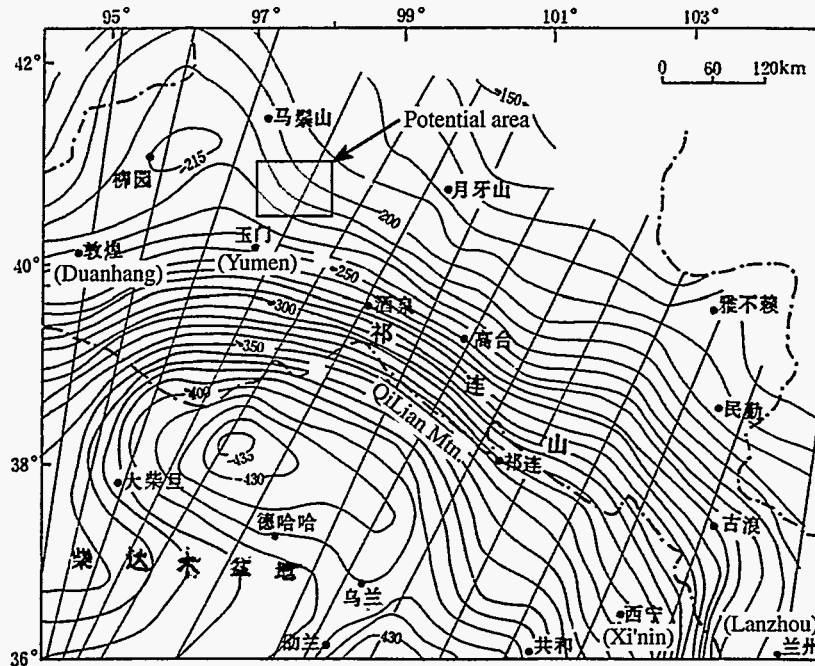


Figure 6.5. Regional magnetic anomaly map of northwest Gansu, China.

earthquake in Mingle County in 1790; the $M=7 \frac{1}{2}$ earthquake in Shandan County in 1954; and the $M=6$ earthquake in Gaotai County in 756.

Neotectonism and Tectonic Stress Field

Neotectonism refers to the crust tectonic movements since the Tertiary, including the horizontal and vertical movement of the crust, volcanism, earthquakes and slides, etc. According to the neotectonic characteristics, the western Gansu Province can be divided into three parts, namely: the Qilianshan blocking and intensive uplifting region; the Corridor depression region; and the Beishan weakly uplifting region (Fig. 6.7). The selected area for the HLW repository is located within the Beishan weakly uplifting region. The land form of the area is characterized by a flatter gobi and small hills with elevations above sea level, ranging between 1000 and 2000 m. The height deviation is usually several tens of meters. Since Tertiary time, it is a slowly uplifting area without obvious differential movements. The rate of uplift for the crust in the area is about 0.6 - 0.8 mm/a, much lower than that of the Qilian region (1.5-1.8 mm/a).

Comprehensive analysis of the structural deformation of the Cenozoic faults and folds indicates that the area is undergoing horizontal compression at present, and the principal compressive stress is between 30 and 60

degrees. The data provided by the mechanism at the source of earthquakes show that the direction of the principal compressive stress is about 40 degrees.

The strike of the main faults in the Beishan area is between 95 and 120 degrees. The angle between the direction of the principal compressive stress and the strike of the main faults, which is also called the superimposed fault angle, ranges between 55 and 80 degrees. These are within the range of stable superimposed fault angles, suggesting that the main faults are stable and will not undergo strike-slip displacement.

6.5.2 Regionalization and Evaluation of Crustal Stability

There are nine indices to evaluate the crustal stability of an area, namely: (1) crustal structure and deep-rooted faults; (2) Cenozoic crustal deformation; (3) Quaternary block and faults; (4) Quaternary and modern tectonic stress field; (5) Quaternary volcanoes and geothermal fields; (6) ground deformation and displacement; (7) gravity field; (8) earthquake strain energy; and (9) earthquakes. According to these indices, crustal stability can be divided into four classes: (1) stable region; (2) basically stable region; (3) sub-stable region; and (4) unstable region.

The western Gansu Province can be divided into three

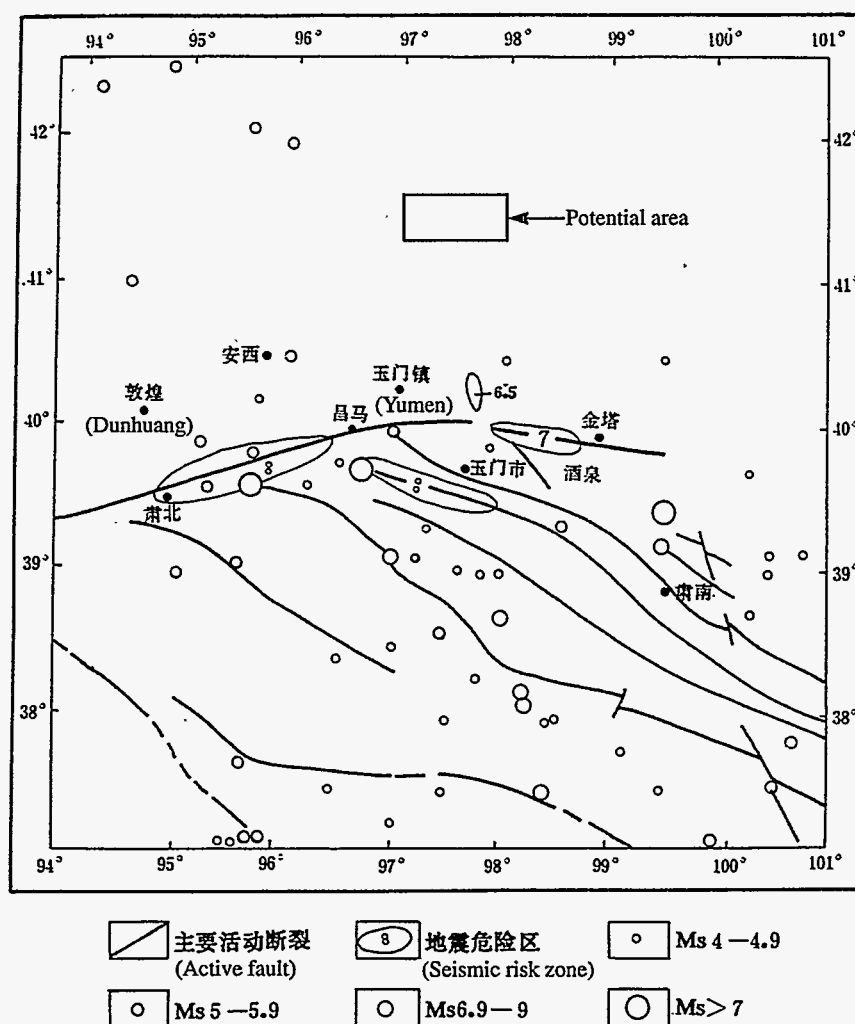


Figure 6.6. Seismic risk zoning of northwest Gansu, China.

regions (Fig.6.8): (1) Beishan stable region; (2) Yumenzhen-Huahai sub-stable region; and (3) Hexi Corridor unstable region. The characteristics of these regions are summarized in Table 6.2. From the table we can see that the Beishan region has a block crustal structure with good integrity and without regional active faults, and it is a slowly uplifting region. The direction of the principal compressive stress in the area is about 40 degrees, and the superimposed fault angles indicate that the main faults will not have strike-slip displacement. There are no gravity steps in the area, and no records of intensive earthquakes either. The earthquake intensity of the area is less than 6. These features show that the crust in Beishan area is more stable than in the southern regions, and is a suitable candidate region for a HLW repository. On this basis, smaller districts can be further selected for detailed site characterization.

Geological work in the Beishan area is at the very beginning stage, and the above data are only preliminary results. In the future, systematic site characterization work will be conducted year-by-year, to determine the suitability of the Beishan area and to select the final site for a HLW repository.

6.6 OTHER STUDIES

The geological disposal of HLW is a long-term comprehensive task. In addition to site selection and site characterization, other studies are also being conducted on:

- Site preselection for an underground research laboratory;
- Experiments on radionuclide migration (laboratory and field);

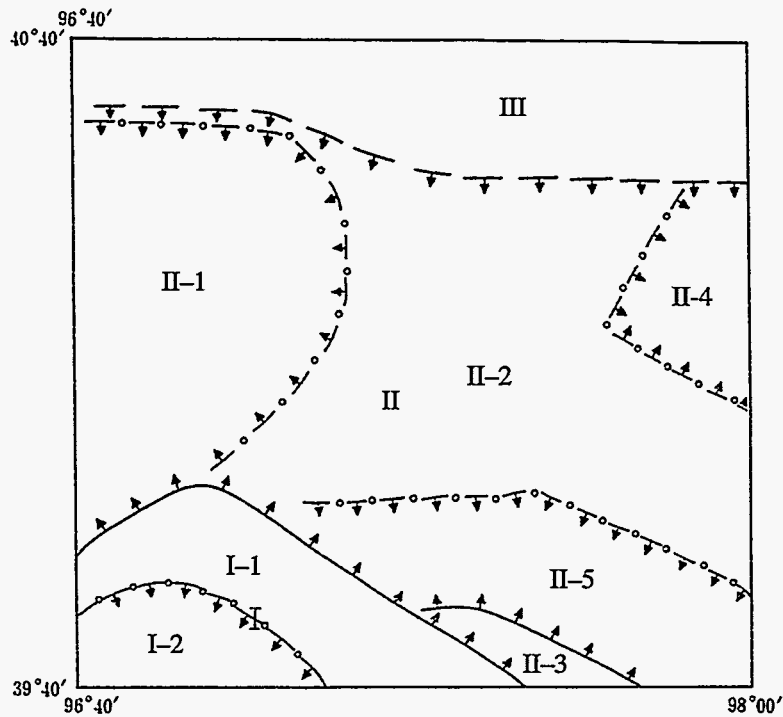


Figure 6.7. Map showing the regions of neotectonics. I - Qilian Mt. intensive uplifting region; II - Corridor depression region, and III - Beishan slight uplifting region.

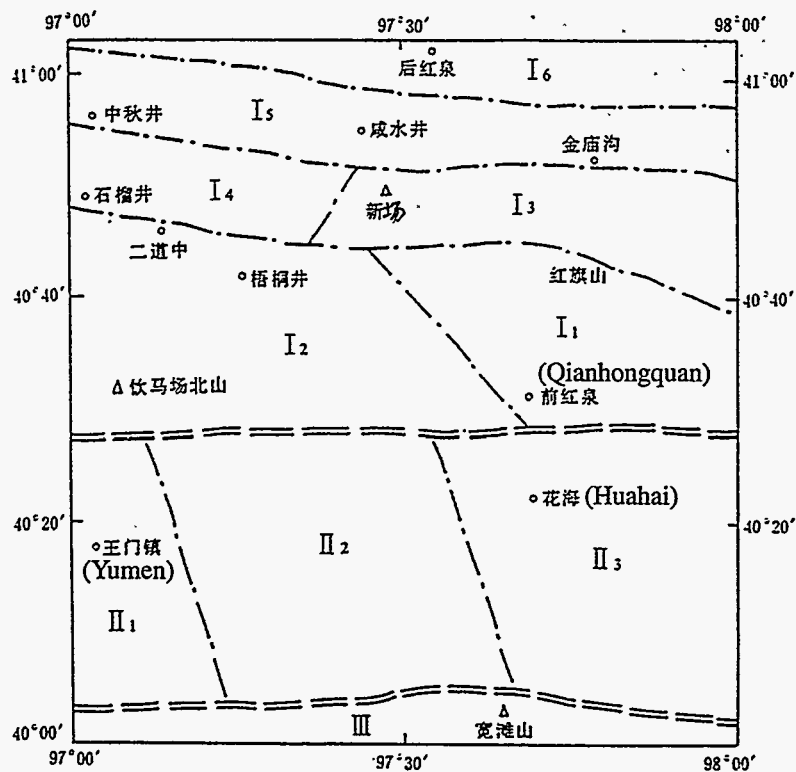


Figure 6.8. Map showing the classification of crustal stability of northwest Gansu Province. I - Beishan stable region; II - Yumenzhen-Huahai sub-stable region; and III - Hexi Corridor unstable region.

Table 6.2 Crustal characteristics in western Gansu Province, China.

Characteristics	Beishan Stable Region	Yumenzhen-Huahai Sub-stable Region	Hexi Corridor Unstable Region
Crust structure and deep fault	Crust is block structure with good integrity, NW-striking basement faults are distributed.	Crust is mosaic structure, with NE- and NW-striking basement faults.	Crust is crushed structure controlled by the north Qilian deep fault and Aljin active fault.
Active fault and Quaternary crustal movement	With few active faults, crustal movements of slowly uplifting region with less than 0.1 mm/a.	With Sanweishan and Aljin active faults, crustal movement is between 0.1 - 3.5 mm/a.	With Aljin active fault, largest crustal movement is 4.7 mm/a.
Superimposed fault angle	55° - 80°	45° - 70°	80°
Gravity field	Gravity anomaly is smooth, gradient is less than 0.5 mGal/km	With regional positive negative gravity anomalies, the gradient is 1 to 2 mGal/km	Located in gravity anomaly step zones with negative gravity anomaly
Seismicity	Largest earthquake (Ms)	5	6.0
	Energy $\sqrt{E}$ (10 $\sqrt{\text{erg}}$)	10.59	25.54
	Frequency (Ms >3.0)	4	2
Possibility for construction of HLW repository	Possible	Not possible	Not possible

- Natural analogues;
- Buffer/backfill materials and their geotechnics;
- Speciation of transuranic elements in solutions;
- Heater test; and
- Models for safety and environmental assessments.

The safe disposal of high level radioactive waste is a worldwide challenging task. Although China has made much progress in this field, there is still a long way to go. For example, a policy act related to nuclear waste disposal should be established, a more effective organization should be formed to promote the required work, and a way should be explored to raise enough money for the safe disposal of nuclear waste.

Information exchange is very important for the disposal of radwaste. China is willing to learn of the successful

experiences in other countries and to strengthen international cooperation. China is also willing to share its own experiences and achievements with other countries, for the purpose of protecting the living environment of human beings and protecting the Earth

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CHAPTER 7

SITE SELECTION OF LOW AND INTERMEDIATE LEVEL RADIOACTIVE WASTE REPOSITORY IN THE REPUBLIC OF CROATIA

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Abstract. The radioactive waste repository site-selection program in Croatia consists of two stages. The first, the site survey stage, consists of: an exclusionary screening of the national territory, an internal evaluation of selected potential areas, and an identification of potential sites, as well as the selection of a few preferred (candidate) sites which would be suitable for further detailed investigations. The second, the site evaluation stage, consists of all necessary field investigations and additional site-characterisation tasks at previously selected preferred sites. Eight potential areas containing 42 potential sites have been selected in Croatia so far. Selection of 3-4 preferred sites is under way. Site selection methodology, including a description of applied exclusionary and comparative criteria, is also presented in the paper. The report is completed with basic information on current Croatian legislation and organisation of a regulatory body in the field, as well as with a brief characterisation of a few more perspective potential sites.

7.1 INTRODUCTION: SOURCES OF RADIOACTIVE WASTE

The necessity of constructing a low and intermediate level radioactive waste (LLW/ILW) repository in Croatia has developed from the fact that there are two main sources of radioactive waste materials. The first group of sources is waste generated in the Republic of Croatia itself, and the second, includes radioactive waste originating from the operation of the Krsko Nuclear Power Plant (NPP). Although the plant is situated in the neighbouring Republic of Slovenia, it represents a joint venture facility of both Slovenia and Croatia. Therefore, Croatia is obliged to find an appropriate solution to dispose of half of all radioactive waste generated during the lifetime of the NPP.

Radioactive waste in Croatia is derived mostly from various nuclear applications: medicine, industry, agriculture and scientific research. In addition to this, there are about 50,000 ionising smoke detectors distributed in 950 buildings and some 500 ionising lightning arresters (protectors) installed on 320 buildings in the country. However, the total amount of radioactive waste which has been generated in Croatia so far is not more than 80 m³, and its estimated gross activity is 2.3×10^{12} Bq. The waste is composed of radionuclides like ^{152,154}Eu, used in ionising lightning arresters; ²⁴¹Am, installed in ionising smoke detectors; ¹⁹²Ir, ⁹⁰Sr, ⁸⁵Kr and some others,

used in measurement and processing techniques in industry; ¹³⁷Cs and ⁶⁰Co, used in numerous diagnostic and therapeutic methods in medicine, etc.

Basically, there are three radioactive waste disposal approaches being practised in Croatia. The first, which refers to hospitals and research laboratories, is an adequate storage of waste until its activity falls to the background level, and after that it is treated as common waste. The second approach is related to waste types containing long-lived radionuclides, which are being properly stored in two temporary storage facilities at scientific institutes "Ruder Boskovic" and the Institute for Medical Research and Occupational Health (both are situated in Zagreb, the capital of Croatia). According to available data, there are some 500 institutions including more than 5,000 persons that are professionally in direct or indirect contact with radiation sources in Croatia.

The Krsko NPP is obviously the greatest producer of all radioactive waste expected to be disposed of in Croatia. Since the plant started operation in 1982, some 2,000 m³ of LLW/ILW with a total activity of about 3.6×10^{13} Bq have been generated so far. However, it is realistic to expect some 8,500 m³ of LLW/ILW to be generated in the lifetime of the NPP. The total activity generated during the plant lifetime, could reach an estimated 1.5×10^{14} Bq. In addition, roughly 11,000-12,000 m³ of decommissioned waste is expected to be produced in the

plant by the end of its operation. This type of waste is supposed to be composed of 53% LLW, 36% ILW and 11% high-level waste. The prevailing radionuclide is ^{60}Co , which is responsible for about 90% of the total activity of the waste. It is expected that Croatia will be responsible for final disposal of some 10,000 m³ of LLW/ILW, i.e. one half of the total LLW/ILW generated during the lifetime of Krsko NPP.

7.2 ESSENTIAL STRATEGIC ISSUES IN RADWASTE MANAGEMENT IN CROATIA

The strategy on radioactive waste management in Croatia was originally drafted by the APO - Hazardous Waste Management Agency in 1992. It was recognised then that only a systematic and well-organised program, which would be based on responsible treatment with radioactive materials and tightly related to regulatory bodies and current legislation, can provide an acceptable approach to safe operation of nuclear facilities and radiation sources in different nuclear applications.

Basically, the strategy as developed in Croatia, includes the following topics, i.e. tasks to be regularly and continuously practised:

- identify all sources and precise quantities of radioactive waste in Croatia, as well as create and maintain an inventory of radiation sources and radioactive waste materials;
- define a legal framework, i.e. the system of responsibilities;
- establish the financing of a national radioactive waste program;
- introduce and, if necessary, improve existing legislation and regulations in the field of radioactive waste disposal;
- develop the LLW/ILW repository, including all necessary activities like site selection, technical design, safety analysis etc.;
- foster public relations; and
- give support to other radiation safety related actions and programs.

The strategy has been rearranged according to existing IAEA documents, and is expected to be modified in the future according to forthcoming requirements and recommendations of this international agency.

7.3 LEGISLATION AND REGULATORY FRAMEWORK

Regulations concerning radioactive waste management,

which are temporarily implemented in the Republic of Croatia, have been partly taken over from the ex-Yugoslav legislation. In general, these regulations have been established according to world-wide practice and support other regulations concerned with environmental protection or the management of other wastes. The basic regulation is the, "Law on Ionising Radiation Protection and Special Safety Actions in Nuclear Energy Implementation", issued in 1984. From this law, 17 regulations and codes of practice have been subsequently derived. The new Croatian law on radiation protection and nuclear safety is expected to be approved by the end of 1996.

Documents to be emphasized here, due to their particular importance in the field of site selection and radioactive waste repository construction and operation, are "Code of Practice on Conditions of Locating, Construction, Start-up and Operation of Nuclear Facilities", "Code of Practice on Standard Format of Safety Report and Other Documentation Needed for Safety of Nuclear Facilities", as well as "Code of Practice on Methods of Collecting, Account, Processing, Storing, Final Disposal and Release of Radioactive Waste Substances in the Environment. (all of them were issued in the period 1986-88). These regulations went into effect according to the "Law on Taking Over the Federal Laws in the Field of Health Protection, Applied in the Republic of Croatia as Republic Laws".

A national regulatory body organising and controlling radioactive waste management, as well as radiation protection issues, has not been established in Croatia as a single institution covering all related issues. It consists of sections of three separated governmental entities: the Ministry of Health, the Ministry of Economy, and the State Directorate for Environmental Protection. Unfortunately, there is no permanent body in Croatia which would co-ordinate activities of these ministries in the field. The Sanitary Inspectorate, as a section of the Ministry of Health, is the competent national authority for radiation protection. The Ministry of Economy, i.e. Department of Nuclear Safety, is the competent national authority for siting, construction, start-up, operation and closure of nuclear facilities. The competence of the State Directorate for Environmental Protection is directed to issues related to environmental clean-up actions of contaminated sites, hazardous waste management, etc. It should be added that a few other ministries (Transport, Finances, Interior, etc.) are responsible for licensing particular activities, which are incorporated in

radioactive waste management and cover the transportation, import-export, release of effluents and some other issues.

7.4 SITE SELECTION METHODOLOGY: STRUCTURE OF SITE SELECTION PROGRAM

7.4.1 Concept Description

The global concept of the Radioactive Waste Repository Project in Croatia consists of several interrelated main task groups. Besides site selection, it also comprises licensing, technology & design development, safety assessment, economic evaluation, transportation analysis and waste characterisation. The whole project is supported by particular activities related to development of legislation and regulatory body organisation. Since there is an urgent economic need to ensure additional energy sources in Croatia, the site selection of thermo-electric- and nuclear power plants is encompassed by the same program as well.

The site selection includes two stages: the first, site survey stage (Fig. 7.1), terminating with the inclusion of candidate sites into the Physical Plan of Croatia; and the second, site evaluation stage, aimed at defining the final repository site through field investigations and other necessary actions.

The first part of site selection, i.e. the site survey stage, is currently under way. It includes the actions that are extremely sensitive since defining site selection methodology and criteria, as well as achieving political and public acceptance for repository siting, have to be completed before preferred (i.e. candidate sites) will be identified and included in the Physical Plan of Croatia and, thus, become available for further field investigations. The planned activities are projected to be performed in two phases: (1) regional analysis and selection of potential areas; and (2) selection of preferred sites (Fig. 7.1).

In other words, the philosophy of site selection is, at first, to define exclusionary criteria for the global reconnaissance of Croatia in order to find potential areas. After comparative and additional exclusionary criteria are defined, potential areas will be subjected to more detailed evaluation designed to identify a number of potential sites. Through a comparison of potential sites and their internal characterisation, a few preferred sites will be evident. These, preferred (or candidate) sites are finally supposed to be included in the Physical Plan of

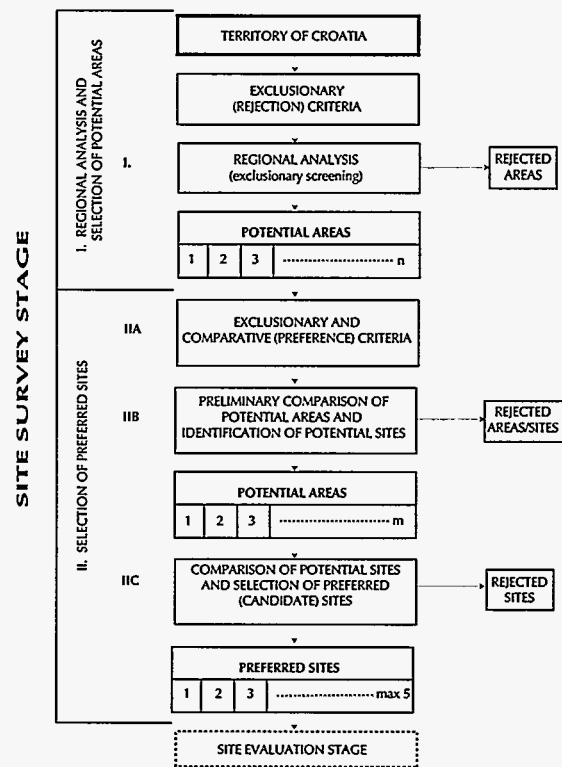


Figure 7.1. Site selection procedure as applied in site survey stage.

Croatia. In the second stage, detailed site investigations will be worked out at two or three preferred sites, which will result with the identification of the final repository site.

In accordance with the above mentioned, it is necessary to clarify terminology involved in referring to selected areas i.e. sites: *potential areas* represent larger areas (100-600 km²), characterised by acceptable isolation properties; *potential sites* are smaller homogeneous areas (5-20 km²), derived from potential areas, which are favourable for siting a radioactive waste repository, and finally, *preferred sites* are small areas (2-20 km²), highly acceptable for the repository siting and convenient for inclusion in the Physical Plan of Croatia¹.

As shown schematically in Figure 7.1, the site survey stage consists of two phases. It could be described in more detail as follows:

- *Regional analysis*, terminating with selection of potential sites, represents the first phase of the site survey stage. It is based on an assessment of the whole territory of Croatia using selected exclusion-

ary criteria ("exclusionary screening"). Areas which do not meet the requirements, defined by at least one of these criteria, are eliminated. Remaining areas are designed as potential areas for further analyses. Regional analysis is based on appropriate information derived from topographic and other thematic maps of Croatia on the scale 1:300,000.

- In the second phase - *selection of preferred sites* - all previously selected potential areas are checked by the exclusionary criteria, and then evaluated on the basis of more detailed data and large scale maps (1:100,000). Comparative criteria are applied to both potential areas and potential sites in order to identify potential sites and preferred sites, respectively. This task is divided into three sub-phases as follows.

7.4.1.1 Selection of Parameters and Criteria.

Proposed parameters and criteria, applied in the identification, selection and comparison of potential sites, are defined by a special team of experts, composed of specialists from different fields of interest (from geology to sociology). Both exclusionary and comparative criteria were officially published in the Croatian official gazette "Narodne novine", No. 78/92. Comparative criteria are generally presented as requirements for achieving a certain goal or a desired state. These goals can be defined as desirable conditions, and if a desirable condition can not be achieved, the criteria should describe the degree of acceptability (i.e. to what extent does the solution approach desirable conditions). The following four groups of comparative criteria have been formed in accordance with basic aspects or dominant characteristics of the criteria involved:

- Engineering aspects.** Criteria comprised by this group show whether the engineering requirements for acceptable radioactive waste disposal are met. Emphasis is placed on the economic issues of facility construction and operation. Preference is given to site characteristics which enable simpler and, thus, economically more acceptable solutions. Characteristics of the site can also affect, to a lesser extent, certain safety aspects of the facility, but these can be successfully compensated by engineering interventions. Regarding this comparative criteria group, sites requiring simple and less expensive engineering solutions are preferred.
- Safety-related aspects.** In this group are collected criteria needed to determine whether the safety requirements for construction and/or operation of the

facility are met. Concordance with safety requirements is checked during all phases of the site selection program, and is very much evident in the licensing procedure of the facility. Emphasis is placed on evaluating the physical properties of an area that could have negative effects on facility safety. However, some site characteristics could have an impact on the choice of additional needed engineering solutions that can influence on cost-benefit issues of construction and operation. Regarding this group of comparative criteria, preferred sites are those where facility safety is derived from more convenient physical (natural) characteristics of the site, requiring a minimum of engineering intervention.

- Environmental impact and acceptability in the immediate site area.** This group includes comparative criteria showing whether the safety requirements, concerning the impact of the facility on the immediate environment, are met. Emphasis is placed on the environmental impact of the facility during its regular operation as well as in cases of possible accidents. Site characteristics can also have an impact on the degree of social acceptance. Concordance with safety requirements must be confirmed throughout all phases of site selection, and it will be evident in corresponding documentation (e.g. study on environmental impact assessment, safety reports, site permits etc.). Preference is given to those physical (natural) site characteristics which provide less impact on the environment, as well as to existing and planned land use types which could act positively on the safety and acceptability of the site.

- Acceptability of the facility site in the broader area.** This group consists of comparative criteria that assess the possible impact of the radioactive waste disposal facility on the broader area. Emphasis is placed on an analysis of present and planned land use types, as well as on the degree of social acceptance regarding possible changes in the value of the area. Preference is given to present and planned land use types causing less conflict and therefore having a greater social acceptability, as well as to physical characteristics that provide milder environmental effects resulting from the facility operation.

Comparison of potential sites: method of weighted criteria

In this phase, it is necessary to choose the most appropriate method of site evaluation and comparison. There

are several techniques and methods in world practice. On the basis of experience acquired in Croatia and Slovenia in the field during the last few years, a multiple criteria analysis has been chosen as the most effective. In particular, the method PROMETHEE (i.e. "Preference Ranking Organisation Method for Enrichment Evaluations"), created by J.P. Brans and P. Vincke, has been applied in our case. The method represents a computerised analysis of a multiple criteria technique and decision-making methods. Thus, objectivity in site selection and assessment has been successfully achieved. The method is based on the application of numerous criteria in order to express interrelations among alternatives, indicating a group of "better" solutions.

The relative significance of each criterion is expressed by assigning to it a corresponding weighting factor. The values of the weighting factors are defined by applying the rating method, and are based on decisions of the experts. After discussion, members of the expert team propose weighting factors for all comparative criteria. As result, a special co-ordinating group adopts the final list of weighting factors (as is presented in Table 7.1; see the section "Comparative Criteria"). It is obvious from the Table that the expert team concluded that criteria group C ("Environmental impact and acceptability in the immediate site area") is the most important with a total weighting factor for this group of 52.5%. This is followed by the group B ("Safety related aspects") with a 30.0% share. The acceptability of broader site area (group D) is expressed by a total weighting factor of 9.5%, since it is assumed that LLW/ILW repository will have almost no impact on the broader site area. Finally, the importance of engineering aspects is estimated to be only 8% because it is expected that the repository would not require considerable civil-engineering interventions.

7.4.1.2 Assessment and Comparison of Potential Areas and Identification of Potential Sites

In order to get more precise information, the first task in this sub-phase is to check on the exclusionary criteria application which would be based on more detailed maps (on the scale of 1:100,000). Geologic characteristics, i.e. engineering/geologic properties - including lithological and geomorphologic, tectonic and seismic, as well as hydrogeological characteristics of the selected sites, are of special interest.

7.4.1.3 Assessment and Comparison of

Potential Sites Followed by Selection of Preferred (Candidate) Sites.

In this sub-phase, more detailed data on sites, previously chosen in sub-phase 7.4.1.2, are collected in order to perform a comparative assessment of their acceptability. The on-site investigation of all potential sites should be carried out, and the exclusionary criteria are supposed to be checked once again. In the field of potential sites, the previously determined reference points should be re-evaluated. With regard to basic safety site characteristics (lithology, hydrogeology, risk of flooding), a certain number of potential sites is expected to be excluded due to their lower quality, by comparison with the others. It has already been decided that not more than 3-5 preferred (candidate) sites will finally be proposed for further detailed on-site investigations.

The final comparison of potential sites, as well as the final selection and proposal of preferred sites, will be performed after validation of both criteria and weighting factors by a competent governmental/parliamentary body. Comments on the involved criteria that would probably result from public debate and discussions with experts will be thoroughly re-examined afterwards by members of the expert team. If agreement is reached, these comments will be accepted. In that case, the main sections of the site survey procedure will be reanalysed.

7.5 SITE SELECTION AS A MULTIPLE CRITERIA ANALYSIS

7.5.1 Some Basic Facts about Croatia

The Republic of Croatia (56,538 km²) is situated in the southern part of central Europe. It includes three major physical-geographical regions: Pannonian basin, Dinaric Alps and the Adriatic coast. As part of former Yugoslavia, it proclaimed its independence in June 1991. There are about five million inhabitants living in Croatia, with an average population density of 80 inhabitants per square kilometre. Due to its unusual shape, the total length of the Croatian border is very long - 2,100 km. The neighbouring countries to Croatia are Slovenia, Hungary, Serbia, Bosnia-Herzegovina and Montenegro, as well as Italy (the border with Italy runs along the Adriatic sea). The major Croatian cities are Zagreb, the capital (900,000 inhabitants), Split (250,000), Rijeka (200,000), Osijek (120,000), Zadar (80,000) and Pula (70,000) (Fig. 7.2). Farming, forestry, fishery, industry, shipbuilding and tourism are the main economic activities. Industry, including mining and

Table 7.1. List of comparative criteria and their weighting factors.

Group: Percent:	A 8.0%	B 30.0%	C 52.5%	D 9.5%	TOTAL 100%
1. <u>Transportation</u>					<u>3.7%</u>
1.1 <i>Transportation or radioactive waste</i>			C.1.1. - 3.7		
2. <u>Meteorology and hydrology</u>					<u>14.3 %</u>
2.1 <i>Hydrological issues</i>		B.2.1 - 7.5	C.2.1 - 3.2		
2.2 <i>Meteorological issues</i>		B.2.2 - 2.8	C.2.2 - 0.8		
3. <u>Geology and seismology</u>					<u>35.8%</u>
3.1 <i>Seismotectonics and seismics</i>	A.3.1 - 4.0	B.3.1 - 5.9			
3.2 <i>Soil mechanics and slope stability</i>	A.3.2 - 4.0	B.3.2 - 9.8			
3.3 <i>Hydrogeology</i>			C.3.3 - 12.1		
4. <u>Demography</u>					<u>5.4%</u>
4.1 <i>Population density</i>			C.4.0. - 5.4		
5. <u>Present and planned land use types</u>					<u>22.2%</u>
5.1 <i>Settlements</i>			C.5.1 - 4.4	D.5.1 - 3.5.	
5.2 <i>Tourism</i>			C.5.2 - 3.3	D.5.2 - 2.5	
5.3 <i>Agriculture</i>			C.5.5 - 2.6		
5.4 <i>Forestry</i>			C.5.4 - 2.2		
5.5 <i>Industry and mining</i>			C.5.5 - 1.1		
5.6 <i>Infrastructure</i>			C.5.6 - 1.5		
5.7 <i>Special purposes</i>			C.5.7 - 1.1		
6. <u>Environmental protection</u>					<u>18.6%</u>
6.1 <i>Protection of natural heritage</i>			C.6.1 - 3.0	D.6.1 - 2.5	
6.2 <i>Protection of cultural heritage</i>			C.6.2 - 1.6	D.6.2 - 1.0	
6.3 <i>Soil properties</i>		B.6.3 - 4.0	C.6.3 - 2.4		
6.4 <i>Bio-ecological values of the site</i>			C.6.4 - 2.5		
6.5 <i>Radiological aspects</i>			C.6.5 - 1.6		

energy production, produces 44% of the national gross income.

7.5.2 Geological Background

Sedimentary rocks prevail in the geologic structure of Croatia, occupying 95% of its surface lithology. Moreover, it should be emphasized that the distribution of Mesozoic carbonate rocks, like limestone and dolomite, is the leading rock type throughout the southern part of the country (i.e. south from Karlovac.) The morphology of this area is characterised by karst (Fig. 7.3), occurring in two basic varieties: shallow karst, covered by soil in the interior parts, and thick, exposed karst stretching along the Adriatic coast. An irregular

hydrogeology and very sensitive mechanisms have a remarkable impact on the quality of surface- and ground-water and control some specific bio-lithological processes (e.g. formation of travertine). Consequently, a lot of human activities being practised in the area eventually leads to considerable environmental pollution.

In the northern part of the country in the Pannonian basin, fluvial, erosional and aeolian clastic sediments are dominant, particularly in the lowlands along the rivers Sava and Drava, as well as in the east Croatian plain. The central Slavonic massifs (Papuk, Krndija, Psunj, Pozeska gora), in the heart of northeastern Croatia (known as Slavonia), are mainly composed of old Paleozoic igneous (granite, basalt, etc.) and meta-

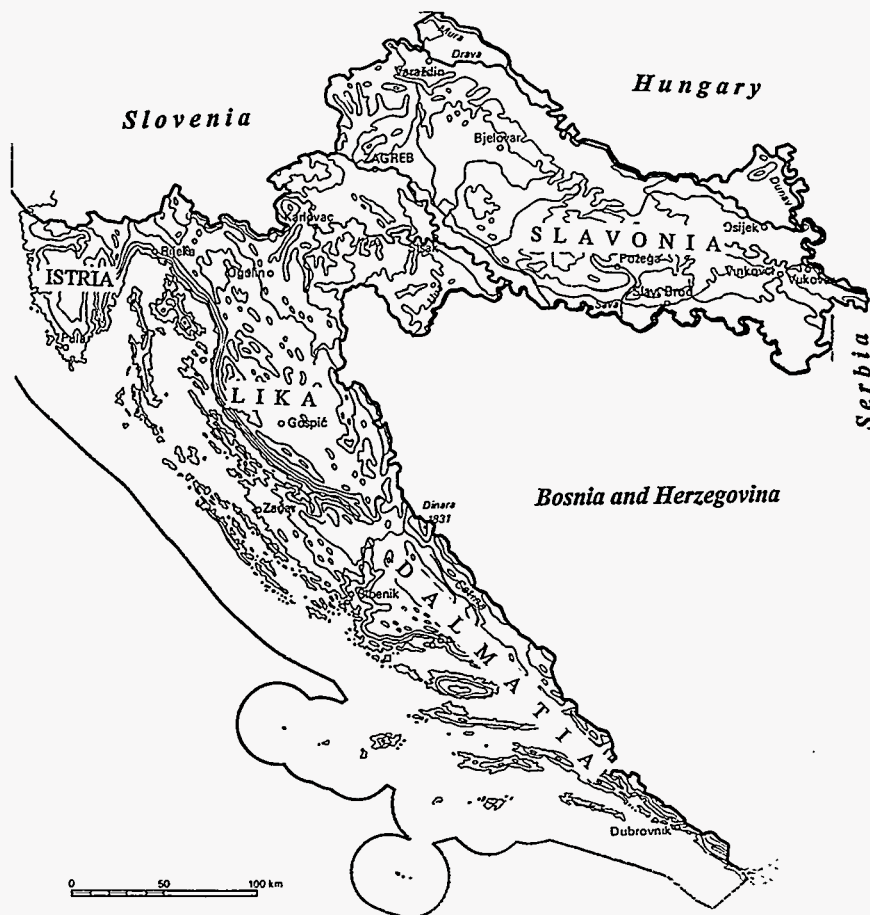


Figure 7.2. Croatia with its major cities.

morphic rocks (crystalline schists, gneiss, etc.) (Fig. 7.3).

The territory of Croatia is an unstable area from the standpoints of both tectonics and seismicity. Several major longitudinal faults run in a NW-SE direction, in both the northern and southern parts of the country. Where they intersect, transverse faults are in many cases characterised by geothermal springs. Earthquakes as intensive as VIII-X MCS can be expected in most of the Adriatic coast region (southern Dalmatia, in particular), but they can also occur in some areas of northwestern Croatia.

During site selection for a radioactive waste repository, attention should be paid to both repository design options and available rock types. The leading principle in both cases is to ensure environmental safety, and not to save money. Almost half of Croatia is not convenient for a repository siting due to the prevailing carbonate lithology, karst morphology and the consequent irregular circulation of groundwater. Since the remaining flatlands

are generally unsuitable because of major infiltration with high water-tables (along the rivers Sava, Drava and Danube), the areas of interest are the previously mentioned mountains of the country's interior, Papuk, Krndija, Psunj and part of Bilogora as well as Moslavačka gora, that is situated somewhat to the west. All these mountains, except Bilogora, are horst-structures composed to a great extent of granite, gneiss and schist².

7.5.3 Site Acceptability Assessment

In the site selection process, it would be insufficient to locate only a host-rock capable of providing waste containment, i.e., to keep water away from the waste. According to the accepted approach, it is recognized that the entire system, i.e. waste form and package, host-rock, geological formations of the broader area, and environment of the region, should provide waste containment. In keeping with this philosophy, the applied criteria should address all site characteristics that contribute to waste containment and insulation. These characteristics

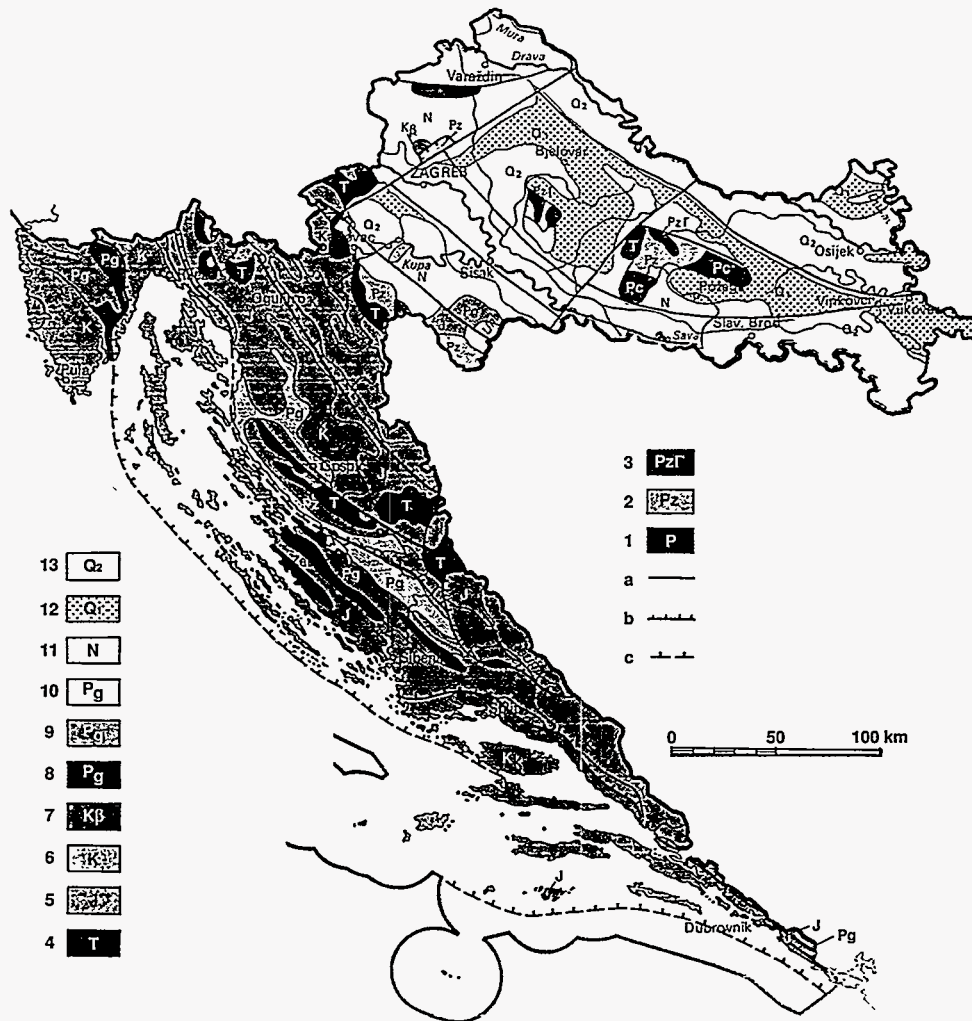


Figure 7.3. Geologic map of Croatia: 1- Precambrian (metamorphic rocks); 2 - Paleozoic (clastites, additionally carbonates); 3 - Paleozoic (igneous rocks: granite); 4 - Triassic (carbonates, add. clastites); 5 - Jurassic (carbonates, add. igneous clastites); 6 - Cretaceous (carbonates, add. clastites/flysch); 7 - Cretaceous (igneous rocks: basalt); 8 - Paleogene (limestones); 9 - Paleogene (clastites, flysch) 10 - Paleogene (limestone clastites, limestones); 11 - Neogene (clastites, limestones); 12 - Pleistocene (clastites/mostly non-cemented); 13 - Holocene (clastites/mostly non-cemented.) Tectonics: a - normal faults; b - reverse faults and thrusts; c - reverse faults and thrusts (submarine).

include geotechnical and socio-economic concerns. In the application of these criteria, greater consideration should be given to those factors that directly influence the safety of the repository than to those criteria which affect only repository cost and timeliness.

In the final analysis, repository licensing and operation can not be performed until it is demonstrated that the total waste disposal system, including the waste form and its packaging, design of engineered facilities and barriers, as well as the multiple natural barriers, will adequately protect public health and safety and preserve the

quality of the environment³.

7.5.4 Exclusionary Criteria

There are ten exclusionary criteria to be applied in the first phase of the site selection process, i.e., in a regional analysis of the whole territory of Croatia, where the aim is to reject all areas that do not meet requirements of these criteria. The exclusionary criteria are divided, similarly to the previously discussed classification of comparative criteria, into four groups: A - Engineering aspects; B - Site safety related aspects; C - Site accept-

ability; and D - Facility safety. These four aspects involve three basic principles for repository siting: cost-benefit ratio, acceptability and safety. The following is a brief description of each criteria with examples of the excluded areas that result when the territory of Croatia is analyzed.

1. Meteorological and hydrological criteria: Flooding (Group D)

All natural floodplain areas excluded (assuming repeat periods at 1,000 year intervals), regardless of whether they are protected or not.

Comment: The LLW/ILW repository must be situated beyond the reach of floods. Hence, all natural floodplains, as well as those areas where accumulations of water are planned, are excluded. Areas, where it is not likely to prove a low risk of flooding by additional investigations, are also excluded. The risk of flooding is supposed to be studied throughout the site selection program.

Excluded areas: Large lowland zones along the major Croatian rivers of Sava and Drava, as well as the Danube in Baranja region; and numerous sinks in karst regions, which are characterised by seasonal flooding.

2. Geology and seismology: Seismotectonics (Group A)

Areas with maximum potential earthquake intensity equal to or higher than IX MCS, are excluded.

Comment: Elimination of areas that are potentially affected by strong earthquakes is also safety related and should be thoroughly evaluated in further investigations. From technical and economic viewpoints, the cost of facility construction increases exponentially as the expected earthquake intensity increases; therefore, the expected maximum intensity IX MCS has been taken as the highest acceptable value.

Excluded areas: Most of southern Croatia (Dalmatia), including the coastal zone, Kvarner bay in the north Adriatic, as well as the so-called "Balaton morpho-lineament", i.e., the mountains of Medvednica and Kalnik in northwest Croatia. Some locations in northeast Croatia (Slavonia) are also excluded by this criterion.

3. Geology and seismology: Neotectonics (Group A)

Zones characterised by known active faults are excluded.

Comment: It is known that in neotectonically active areas, as well as in the vicinity of regional and even local active faults, dislocations and rock cracking are possible. These events could cause damage to a waste disposal facility. This safety related criterion is also supposed to be applied (or re-checked) in subsequent phases of the site selection program. In addition it should be mentioned that the term "active fault", as used here, is related to a zone that is a few kilometres in width and includes two or more parallel faults. Earthquakes with magnitudes 5.5 - 7.0 can occur along these faults.

Excluded areas: Southern Croatia, including the coastal zone, Kvarner bay, parts of northwest Croatia, as well as some spots in northeast Croatia - Slavonia.

4. Geology and seismology: Lithology and geomorphology (Group A)

Option 1: Shallow ground disposal: *Areas characterised by an increased erosion rate due to lithology (prevailing rock types) and/or relief dynamics, as well as areas composed of rocks which are unstable under natural conditions (e.g. which are not resistant to weathering etc.) after the completion of civil-engineering works, are excluded.*

Option 2: Tunnel-type disposal: *Areas characterised by land slides and rock falls are excluded if it is thought that these processes could pose a hazard to repository structures.*

Comment: Lithologic, geomorphologic and geotechnic characteristics, along with hydrogeological properties of an area, are considered the most important criteria related to the siting of an LLW/ILW repository. The upper Pliocene and Quaternary clays and Neogene marls (lower Pontic "Abichi" sediments, in particular) are considered the most suitable for a shallow-ground facility siting in Croatia. For the tunnel-type repository, areas composed of granites and some other igneous rocks are most suitable. Some metamorphic rocks like gneiss and some types of schists could also be used for this purpose. Areas which do not meet these requirements are excluded.

Excluded areas: Lowlands along the Sava and Drava rivers in the interior of Croatia, due to possible liquefaction caused by earthquakes; hills which surround the mountains of Zumberacka gora, Medvednica, Kalnik and Ivanscica in northwest Croatia and are composed of Neogene and Quaternary sands, clays and marls; flysch belts in the Istrian peninsula (west Croatia), parts of allu-

vial zone of the Sava river and its tributaries, and some sections of river valleys in Istria and Dalmatia and few other spots in the karst regions.

5. Hydrogeology: Protection of water-bearing layers (Group B)

Areas containing protected sources of drinking water are excluded. In order to preserve groundwater from possible radioactive pollution, a disposal facility can not be situated in an area containing significant water-bearing layers of any type.

Comment: Hydrogeologic properties of any potential site significantly influence the selection of repository design, and also represent specific mechanisms for the assessment of possible environmental pollution. Therefore, areas of high risk for groundwater pollution are excluded at the very beginning of the site selection program. In the case of a tunnel-type repository, suitable areas are those which are composed of solid, primarily impermeable rocks having no secondary porosity. For shallow-ground disposal, the more preferable areas are composed of thick clays and marls without major aquifers. The possible impact on springs and wells, in addition to the necessary protection measures, are examined in all further site specific investigations.

Excluded areas: Parts of the country characterised by major aquifers where groundwater is not protected by near-surface layers or by formations of high porosity. This means almost all of the lowlands along the rivers of Mura, Drava and Danube, the extreme upstream and downstream sectors of the Sava river zone, as well as practically the entire karst area, which represents in fact the southern half of the country.

6. Demography: Population density (Group C)

Areas characterised by a population density of 80 inhabitants per square kilometre (i.e., the average value for Croatia) or more, within a 20 km radius around the facility site, are excluded.

Comment: One of the preferred factors in lowering the risks of nuclear facilities to human health and environmental preservation is to have as low a population density as possible. For that reason the more densely populated areas of Croatia are excluded. The population density in the vicinity of a facility will be re-evaluated in subsequent phases of the site selection program.

Excluded area: Broad areas around major Croatian cities

and the towns of Zagreb, Split, Rijeka, Osijek, Zadar, Pula, Dubrovnik, Karlovac, Sisak, Varazdin and Sibenik, which are all characterised by population densities higher than 80 inhabitants/km².

7. Present and planned land use types: Special purposes (Group B)

Areas designated for special purposes, including their protected zones, are excluded.

Comment: Certain areas are of special interest for national defence. All areas which are, or could be, in conflict with this criterion are excluded.

8. Present and planned land use: Mining exploration of ores and minerals (Group B)

Areas in zones of present or planned mining including exploration of minerals, gas, oil, coal etc., are excluded.

Comment: Exploration of ores and minerals could have an impact on the LLW/ILW disposal facility safety, and in this way make the potential site economically unfavourable. Some limited areas along the Sava and Drava rivers have been excluded by this criterion due to existing or perspective exploration of oil and gas.

9. Environmental protection: Protection of natural heritage (Group B)

National parks, natural parks and other specific natural areas of common interest, are excluded.

Comment: In early phases of the site selection program, it is necessary to identify areas that are protected as a natural heritage and are therefore not suitable for siting a LLW/ILW disposal facility. This criterion is closely related to the requirements defined in the Natural Protection Law, which mentions specific, ecologically sensitive areas that should be continuously protected.

Excluded area: National parks (Brijuni islands, Risnjak mountain, Plitvicka jezera lakes, Velebit mountain, Kornati islands, Krka river and part of Mljet island), natural parks (parts of some mountains, rivers, swamps, islands, etc.) and other significant natural reservations (landscapes, forests, etc.)

10. Environmental protection: Protection of cultural heritage (Group B)

Areas containing monuments of cultural heritage which are registered in the List of World Cultural and Natural

Heritage, as well as those that are of an extraordinary national importance, are excluded.

Comment: It is necessary at the very beginning of the site selection process to define areas which are protected as monuments of cultural heritage, since they have to be avoided as potential sites for the LLW/ILW disposal facility. The term "cultural heritage", as used here, is applied not only to an object of interest itself, but also to the surrounding area.

Excluded area: Monuments of cultural heritage presented on the List of World Cultural and Natural Heritage (e.g. Diocletian's Palace in Split and the old town of Dubrovnik), larger areas known by their specific landscape, as well as culturally, historically and aesthetically valuable locations.

7.5.5 Comparative Criteria

After potential sites are identified by the process of exclusionary screening (including re-checking of preliminary chosen sites by the same exclusionary criteria, but applied now on more detailed maps), they have to be subjected to a comparative analysis, i.e. an evaluation based on an application of comparative criteria. As already mentioned, these criteria were defined by the expert team members and divided into four aspect groups: A - Engineering, B - Safety, C - Environmental impact and acceptability in the immediate site area, and D - Acceptability of the site, i.e. the facility in the broader area. The criteria were then classified into six thematic groups, and, according to their importance, were given corresponding weighting factors, also defined by the expert team. A total of 28 comparative criteria (see Table 7.1) were applied in the site selection program. Table 7.2 provides a list of topics to which the comparative criteria in Table 7.1 were applied.

7.6 DESCRIPTION OF COMPLETED ACTIVITIES

The activities on radwaste repository site selection in Croatia began in 1988. Until 1991, Slovenia and Croatia had not been proclaimed as independent states, and the preliminary activities on repository site selection in both republics (i.e. states) were managed by the Inter-republic Coordination Commission in order to harmonise the site selection procedures in both countries. In Croatia, the Ministries of Energy and Physical Planning, through the Croatian Electricity Management Board, were committed to the Institute for Urban Planning of Croatia to perform the study "Site Screening, Investigation and Assessment of Site Suitability of Fossil Fuel Power

Table 7.2. Application of comparative criteria.

Identification Number	Comparative Criterion to be applied to:
A.3.1.	Seismic Activity
A.3.2.	Soil mechanics
B.2.1.	Risk of flooding
B.2.2.	Extreme meteorological phenomena
B.3.1.	Neotectonic activity
B.3.2.	Lithology and geomorphology
B.6.3.	Chemical aggressiveness of soils
C.1.1.	Transport of radwaste
C.2.1.	Distance to surface waterways
C.2.2.	Dispersion in atmosphere
C.3.3.	Presence of infiltration
C.4.0.	Population density
C.5.1.	Settlements
C.5.2.	Tourism
C.5.3.	Agriculture
C.5.4.	Forestry
C.5.5.	Industry and mining
C.5.6.	Infrastructure
C.5.7.	Special purposes
C.6.1.	Natural heritage protection
C.6.2.	Cultural heritage protection
C.6.3.	Plant production (soils)
C.6.4.	Bioecological issues
C.6.5.	Radiological issues
D.5.1.	Settlements
D.5.2.	Tourism
D.6.1.	Natural heritage protection
D.6.2.	Cultural heritage protection

Plants and Nuclear Facilities in the Territory of the Republic of Croatia". The goal of the study was the identification of preferred sites for thermal and nuclear power plants, as well as a radioactive waste repository, which might later be nominated for this purpose in the Physical Plan of Croatia. The Institute for Urban Planning created a special team of experts, to define and assess selection criteria, as well as to act decisively in identifying potential areas, potential sites and preferred (candidate) sites. The set of exclusionary criteria was defined by July 1989, and validation of criteria was carried out by the Croatian Government.

Using the method of exclusionary screening for the whole territory of Croatia (Fig. 7.1), the resulting map showing areas which "survived" exclusion of inconvenient regions was obtained, and eight potential areas



Figure 7.4. Locations of eight potential site areas for a LLW/ILW repository.

(Petrova gora, Trgovska gora, Zrinska gora, Bilogora, Moslavacka gora, Papuk-Krndija-Psunj, Pozeška gora, Dilj) were finally identified in autumn 1990 (Fig. 7.4). Collecting additional data on potential areas and defining comparative criteria were the main project activities being worked out during the rest of 1990 up to August 1991. Site selection methodology and criteria were examined by the IAEA Radioactive Waste Management Advisory Programme (WAMAP) in the spring of 1991, and were assessed as high-grade. Since autumn 1991, i.e. after the fall of former Yugoslavia, the newly established APO - Hazardous Waste Management Agency started to manage the remaining part of site selection program in Croatia. On the basis of previously performed actions, it was possible in autumn 1994 to identify 42 potential sites, which are dispersed within the above mentioned eight potential areas (Fig. 7.4). Consequently, the only task remaining in the second

phase of the site survey stage is to select 3-5 preferred sites, which will be suitable for further detailed on-site investigations. This task should be done by the end of 1996.

7.7 CONCLUSIONS

The siting of a radioactive waste repository in Croatia has been adjusted to the requirements derived from physical (regional) planning documentation. The site selection program is composed of two stages: (1) a site survey, terminating with the inclusion of preferred (candidate) sites in the Physical Plan of Croatia; and (2), site evaluation to define the final repository site through field investigations and other necessary activities. There has been very slow progress in carrying out this program due to certain circumstances in the country and the entire region, and the preferred sites will not be defined

before the end of 1996.

The system approach includes a simultaneous preparation of the repository technical design, performance assessment and some additional activities. Furthermore, it would be preferable to find a site that would be convenient for a combined disposal facility, not only for radioactive waste, but also for other types of hazardous wastes. An interdisciplinary approach is applied in the site selection, where all relevant topics from geology to sociology are involved in the program. A standard site screening technique has been applied in this process. The stepwise approach to the site selection is based on validation of every single step (starting from the entire state territory), and is supposed to be terminated with the selection of few preferred sites. The program is based on the implementation of both exclusionary and comparative criteria that have been selected by a special team of experts.

The selection of a radioactive waste repository site is considered as a process leading to an optimisation of land use policy of the country in the light of attaining an optimum method of exploitation of the national resources. In addition, the site selection is conceived as an action supposed to be internationally verified, aiming to strengthen our proclamation that, "We are doing just the same as other countries". It is also worth mentioning that the radioactive waste repository site selection is part of a useful project directed to site selection of nuclear-, coal- and gas-fired power plants. Anyhow, a regularly performed site selection process could be assessed as a prerequisite for possible future nuclear energy program in Croatia.

Considerable effort is being given to a program of providing full, complete, continuous and honest information to the public. Necessary preparations for involvement of local communities into the site selection process have already been completed. Hence, democratisation in the siting process of a radioactive waste repository, as a controversial facility, could be achieved in the best pos-

sible way. It also includes the determination of incentives needed by communities living in the vicinity of the repository. In addition, being concerned of their possible NIMTOO ("Not in my Term of Office") behaviour, we are also very careful, and are doing our best to prevent "premature" exposure of politicians to the consequences of the expected NIMBY effect.

Finally, we are facing the specific problem of some malicious attempts, done mostly by certain politicians, or "experts," to explain the radioactive repository site selection program in Croatia as an action based, above all, on an ethnic criterion. It must be emphasised that in spite of arguments derived from an extremely irrational approach, these accusations could attain the end, which is not, in fact, to stop or aggravate the site selection process itself, but to deteriorate the very sensitive political and military situation in the broader region.

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CHAPTER 8

GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE IN THE CZECH REPUBLIC

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8.1 INTRODUCTION

The Czech Republic has appeared on the map of Central Europe since 1/1/1993 after the split of Czechoslovakia in two parts; the other is the Slovak Republic. With its 10.3 million inhabitants and a territory of 78,864 km², the country is comparable with e.g. Belgium, Switzerland or Austria. The Czech Republic belongs to the more successful transformed states of the former Soviet block: A steady decrease of inflation (9% in 1995), increase of GNP (4.6% in 1995), non-deficit budget and low unemployment (3.5% in 1995) are signs of a stabilized economic situation.

The intensive industrialization of the country requires among other things, a high production of energy: the installed capacity is 13,793 MWe, of which 1,760 MWe is nuclear. Consumption of electric power, some 58 TWh in 1995, is provided from internal resources for 94%, of which nuclear plants provide approximately 21%. This power is produced in NPP Dukovany with four VVER 440 MWe blocks. Another nuclear facility is under construction: the Temelin plant shall operate two VVER 1000 MWe units. After their connection to the grid in 1997-8, the share of electric power produced by NPP should reach almost 45% of the national electric power production, and some coal burning plants will be decommissioned.

8.2 ORGANIZATIONAL STRUCTURE OF WASTE MANAGEMENT

Radioactive wastes are produced and managed in the Czech Republic in three independent fields: uranium mining and milling, nuclear power plant, and other institutions (medicine, research, industry). The government controls all activities through the Ministry of Trade and Industry. The owner of uranium production facilities, DIAMO, is a state enterprise. The state also owns 67.46% shares of CEZ, which is the operator of

Dukovany and Temelin NPPs. The company legally responsible for collection and disposal of institutional waste, NYCOM, is controlled by a "golden" share of 5% by the Czech state as well. Independent supervision of all activities is performed by the State Office for Nuclear Safety which regulates and licenses both from the point of nuclear and radiological safety. The Ministry of Environment indirectly influences these activities, as it is responsible for decisions in the Environmental Impact Assessment procedure.

The waste producers are obliged to treat, condition and dispose all radioactive waste at their own expense. However, especially for disposal activities, the responsibility may be transferred to another licensed organization. This procedure is obligatory for the disposal of institutional waste, as NYCOM is the only licensed operator of repositories for these wastes.

8.3 WASTE PRODUCTION AND MANAGEMENT STRATEGY

The amount and characteristics of radioactive wastes produced in the Czech Republic vary according to the source. While uranium mining and milling produces huge volumes in the tens of millions of cubic meters of low contaminated material, other users of radioactive materials treat hundreds or thousands of tons of medium and highly radioactive wastes.

In the Czech Republic, uranium has been mined in seven regions and in some isolated shafts as well. Since the early fifties, about 100,000 MT of U have been produced. The ore was milled in at least four facilities. Wastes that have been produced during excavation are stored in surface piles. They contain more than 46 million MT of tailings contaminated with 5 - 300 ppm of U and 0.06 - 2.4 Bq/g of ²²⁶Ra. Nearly 57 million m³ of milling waste are stored in tailings ponds; the solid phase is contaminated with 0.3 - 5 mg/l of U, 5 - 30 Bq/g

^{226}Ra , and other chemical and radioactive pollutants. Furthermore, there are some 270 million m^3 of contaminated underground water that must also be treated. Rehabilitation of sites with surface deposits from uranium facilities is in progress; mine tailings are used for closure of abandoned mines while sludge ponds are dewatered and overcovered with low permeable soil layers. This is the basic and quite successful method of environmental protection against an influence of natural radionuclides.

The operation of NPP Dukovany produces annually 400 - 500 m^3 of conditioned low and intermediate level radioactive wastes. The prevailing radionuclides are typical fission products, such as ^{137}Cs , ^{90}Sr , and activation products (^{54}Mn , ^{60}Co). Liquid effluents are evaporated and bituminized while solid wastes are segregated, compacted and, when suitable, supercompacted. Sludges and ion exchange resins are dried and disposed in polyethylene High Integrity Containers. All these wastes are buried in the surface repository at the Dukovany site. It is designed so that it can also accept operational wastes from NPP Temelin; their amount and form after conditioning are basically the same as from NPP Dukovany. As the decommissioning of both facilities generates nearly 50,000 m^3 of wastes acceptable for disposal in this repository, its capacity will have to be enlarged, unless some more volume saving treatment methods are applied. Nuclear power plants, however, also produce wastes that shall be disposed of in a deep geological repository (DGR). The significant part of those wastes are in the form of spent fuel (nearly 3,000 MT) and decommissioning high level waste (HLW, some 20,000 m^3).

Institutional wastes were already produced in the Czech Republic in the 1920's; nevertheless, they have been treated, conditioned and disposed of at a central location since the late 1950's. During this period nearly 3,400 m^3 of wastes with gross activity exceeding 10^{16} Bq were accepted for disposal, currently with an annual increment of several tens of m^3 . The wastes were contaminated mostly by ^{60}Co (54%), ^{137}Cs (37%), ^3H (7%), ^{241}Am (1%), etc. Sealed sources are kept at the storage site, or, when acceptable, grouted in drums with concrete. Liquid wastes are solidified with concrete (in severities by bituminization) and solid wastes are low pressure compacted.

8.4 NEAR SURFACE REPOSITORIES

Intensive utilisation of radioisotopes and nuclear

research facilities required commissioning of repositories able to accept institutional wastes. For this purpose the Hostim repository was the first in former Czechoslovakia which was put into operation. From 1953 until 1965 about 400 m^3 of institutional wastes were placed in two galleries in an abandoned limestone mine several tens of meters below the surface. The predominant disposed radionuclides were ^3H , ^{14}C , ^{60}Co , ^{90}Sr , ^{137}Cs with a total activity 0.1 TBq. Packages with higher activity and long lived nuclides were transferred to other facilities prior to the repository shut down. Currently, backfilling of void spaces in galleries is proposed for stabilization and ultimate closure.

In 1964, a new repository went into operation. It was also situated in an abandoned limestone mine 40 - 60 m below the surface: the Richard II complex was used as an underground military factory during World War II. This facility is designated for institutional wastes with the exception of those contaminated by natural radionuclides. The total activity of 2,700 m^3 of disposed wastes has reached 10^{16} Bq mostly formed by ^{90}Sr , ^{241}Am (both 31%), and ^{60}Co (30%). Approximately 95% of the total activity is in the form of sealed sources, while the main unsealed nuclide is ^3H . The overall available capacity is estimated to be 3,800 m^3 of wastes, although the expansion of disposal spaces for a further 2,800 m^3 has been considered. This reconstruction is strictly opposed by local authorities.

The third repository, Bratrství, is used for wastes contaminated only by natural radionuclides (^{226}Ra , ^{210}Po , ^{210}Pb , uranium and thorium isotopes). The facility was built in an abandoned uranium mine (granitic host rock) in Jáchymov, well-known town where M. Curie-Sklodowska took tailings for her experiments. During its operation, that started in 1974, about 250 m^3 of conditioned wastes were put there. The remaining capacity of 40 m^3 of wastes will be filled within 3-5 years. The major nuclides contained in these wastes are as follows: ^{226}Ra (10^{12} Bq), ^{232}Th (10^9 Bq), and others (10^9 Bq). Some wastes (mainly alpha bearing) are to be transferred to a deep geological repository after it is available.

A surface repository for low and intermediate level wastes has been in operation since 1993 at the Dukovany site. The repository spaces are formed by two double-rows of vaults, the dimensions of each are approximately 6x6x18 m. The existing volume, in 112 vaults of approximately 60,000 m^3 , can be extended by construction of 8 new double rows. The radioactive inventory shall not exceed 10^{16} Bq. The facility has a fully engi-

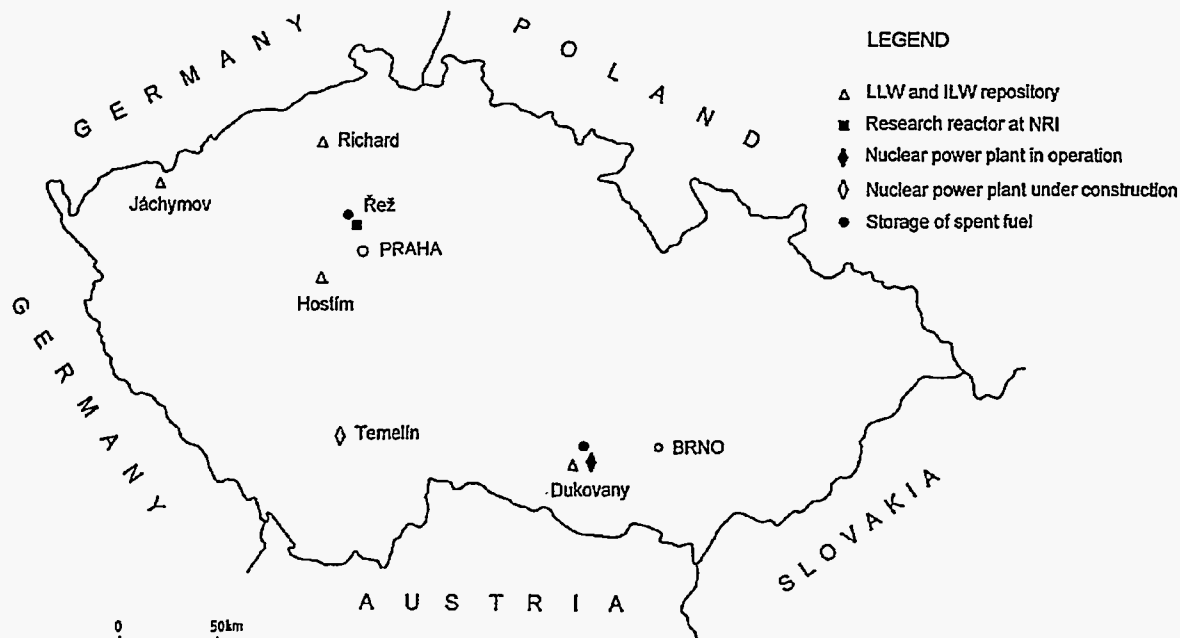


Figure 8.1. Location of nuclear facilities in the Czech Republic.

neered structure; reinforced concrete walls are isolated by asphalt-propylene microconcrete layer. The water movement on site is controlled by three independent drainage systems. A final multilayer capping will be installed after the doublerows are filled with waste. The void spaces in vaults are to be grouted with a concrete mortar.

Geographical locations of all the above mentioned repositories are shown in Figure 8.1.

8.5 SPENT FUEL MANAGEMENT

Spent fuel is not considered to be a radioactive waste in the Czech Republic. However, the producers must deal with it as a high level waste. Production of the spent fuel depends on the time of operation of the nuclear reactors. Provided that each unit will be in operation for 30 years, the Dukovany plant will produce fuel assemblies containing 1,504 MT of uranium metal, while the Temelín facility production will be 1,342 tons. The third producer, the Nuclear Research Institute in Řež, operates two research reactors of which one is used for irradiation (LVR-15 MW) while the other is only a critical assembly for physical studies. At the present time, there are more than 300 bundles of different types in storage at NRI.

The current scheme of the NPP spent fuel management

is based on the assumption that it will be directly disposed of after some 50 years in storage. However, no final decision has been made. Therefore, a dry in-cask storage facility was put in operation at Dukovany in 1995. It uses iron casks CASTOR VVER 440 developed by GNS (Germany) and produced in cooperation with SKODA WORKS Plzeň. Each cask can contain 84 assemblies. The capacity of this facility was limited by a governmental decision that respected the requests of local authorities to 600 MT of heavy metal. This practically means that by 2005, a new storage facility must be operational. Its capacity shall be at least 2,200 MT of uranium, with enough reserve for a considerable period of NPP operation.

Spent fuel from the research reactors is kept in dry storage and a water pool within the NRI. Due to the high enrichment (80, resp. 40 %), it will probably be reprocessed so that the fissile material is under international supervision.

8.6 DEEP GEOLOGICAL DISPOSAL PROGRAM

Some activities aimed at the research aspects of a deep geological repository in former Czechoslovakia started in the mid eighties. Nevertheless, problems concerning disposal of HLW and spent fuel were studied separately in different organizations and institutions until 1992. In 1993, the Nuclear Research Institute Řež plc. (NRI) was

entitled to coordinate the activities which would lead to the development of the Czech geological repository. This year, a general geological disposal program was released and successfully reviewed by a WATRP mission (organized by IAEA) with recommendations for further direction of the program. Since 1994, the Program has been supervised by a Steering Committee of Six Institutions (C6).

The essential technical parts of the deep geological disposal program are:

- siting (and related geological activities such as an underground research laboratory and natural analogue study);
- repository design and disposal engineering;
- development of engineered barriers;
- safety analyses and performance assessment; and
- alternative disposal options (transmutation).

QA/QC, program/projects management and integration, program information systems, and external relations are additional activities of the Program. The Program has been focused mainly on preliminary and generic studies so far, and it considers hard host rock as a most probable option.

8.6.1 Repository design and disposal engineering

Preliminary conceptual disposal system design including infrastructure has been worked out. The present reference design considers two access shafts (one for personnel, one for waste), one ventilation shaft and a system of main and horizontal parallel disposal drifts. Other alternative designs are proposed that differ mainly in access tunnel design (for example spiral and inclined access to the underground). Particular alternative designs were evaluated preliminarily on the basis of safety and feasibility.

An optimization study of spent fuel conditioning prior to disposal indicates a preference for minimum restructuring of fuel assemblies. An encapsulation unit is designed as an integral part of the disposal system at the site. Several repository transport and handling system options have been proposed.

The preferable excavation method for underground spaces has not been selected yet; the importance of the extent of disturbed zones is questionable. The problem is analogous to an underground cavern built for storage of gas; this was mined in granitoid host rock more than 1000 m below the surface in the Příbram uranium min-

ing region. The alternative use of backfill and sealing materials is also studied.

Calculations of radionuclide contents and heat output (ORIGEN code) for spent fuel with different burnups have been performed. According to preliminary heat transfer calculations an optimal configuration for disposal rooms and disposal boreholes was designed.

A cost analysis of the disposal system was also carried out. The objective was to propose an algorithm for determining the waste producers fee for disposal of radioactive wastes (0.05 CZK/kWh). This study estimates an overall disposal system cost of approximately 100 billion CZK (i.e. approx. 3.5 billion US\$).

8.6.2 Development of engineered barriers

Bentonite (and bentonite-based mixtures) was selected as a suitable buffer and backfill material. A bentonite availability study identified many deposits in the Czech Republic; the main criteria considered were material quality and planned volume of buffer and backfill. A preliminary design of a disposal container was proposed by the main Czech steel product manufactures; alternative materials, such as titanium and stainless steel, were also considered.

Planning of experiments, such as spent fuel leaching, engineered barriers degradation, corrosion of disposal container, has started. The main objective of these experiments is validation of models. Both laboratory and field experiments are to be used.

8.6.3 Performance assessment

Performance assessment is considered to be of key importance in the Program because of the necessity to prove long-term safety of the disposal concept. In a preliminary stage, all near-field and far-field features, events and processes (FEPs) have been continually identified, databased and evaluated. Suitability of codes shall also be evaluated. A safety analysis methodology was studied, including methods of probabilistic safety analysis (PSA). In 1995, a study using the Czech format for an Environmental Impact Assessment was performed.

8.6.4 Alternative disposal options

Transmutation technology has been studied as a complementary but not fully replaceable option to the disposal of spent fuel. Preferably, accelerator driven sys-

tems seem to be the most promising. When considering the practical aspects, many unsolved problems have been identified, such as continual hot chemical separations, complicated physical systems, non-verified technology, unresolved benefits and costs. Although mainly generic and system studies were performed, long-term experience of NRI staff with fluorine chemistry and reactor physics as well as the theoretical background of the Nuclear Physics Institute, skills of employees of the SKODA machinery works and promotion of reactor designers speak for reasonability and good starting points for initiation of the respective research and development experiments. Transmutation is a typical problem requiring wide international involvement, and thus, Czech specialists are linked with several US, European and Japanese institutions.

8.6.5 Public/external relations

Taking into account the high population density in the Czech Republic and the deep environmental feeling coming from a damaged natural environment, the strong NIMBY syndrome and general disapproval with the disposal concept are expected. As a consequence, the societal and political factors in a deep geological repository program will be very important.

The communication program is aimed not only to inform the general public but it shall also initiate some direct public participation in decisions. The communication policy is based on open, full and understandable information for the public. Current activities include publication of a series of informative articles in newspapers and magazines, editing of purposeful brochures, preparation of video presentations, presentation of the Program on the conferences and lecturing at universities. RACE methodology (research, analysis, communication, evaluation) is being applied; the final step is carried out in the form of a public opinion poll. Poor knowledge of radioactive waste management rather than dissent from any disposal solution and, surprisingly, general agreement with nuclear power generation are the main findings of the first public opinion polls.

An inseparable part of external relations is cooperation with foreign organizations involved in radioactive waste management, such as ANDRA, GRS, AECL, and ENRESA.

8.6.6 QA/QC

A quality assurance system is being created along with

the quality and management guides/manuals; especially ISO 9,000 and 14,000 are taken into account. The system follows two general directions: QA of the Program management and QA binding technical activities within performance of the Program.

8.6.7 Scope of work in 1996

In 1996, the Program activities are focused on the revision of the Deep Geological Disposal Program. The objectives are to formulate general as well as detailed projects and plans based on evaluation of acquired experience and on information gained since the start of the Program. System re-engineering principles will be explored; they involve the complex, multidisciplinary and time/cost consuming character of the problem to be solved. License, technical and system requirements are being identified along with critical points of the Program. The year 2035 is the main time constraint, when the deep geological repository shall be operational.

8.7 GEOLOGICAL ASPECTS OF DEEP GEOLOGICAL REPOSITORY

8.7.1 Brief Geological History of the Czech Massif

The selection of an optimal geological unit for DGR is, among others, always limited by the geological structure of the territory. Moreover, in the case of the Czech Republic, this fact is underlined by a small areal extent and by a significantly complicated geological structure.

According to the classical geological Stille's division, the Bohemian Massif, belongs to the Meso - Europe, e.g. the vast zone, which was consolidated in the late Paleozoic period during the Hercynian orogeny. Within the European Hercynides, the Bohemian Massif ranks among the Variscides which create partial branches of the Hercynides. The Bohemian Massif, which represents the easternmost known part of the Variscan branch, forms the absolute majority of the territory of the Czech Republic. Brunovistulicum, a block consolidated during the Cadomian orogeny or even earlier, is situated in the eastern part of the territory of the Czech Republic. In the west, this block forms the underlying unit of the eastern part of the Bohemian Massif; in the east, it forms the underlying unit of the West Carpathians, which belong to the Alpine-Carpathian orogenic belt (Neo - Europe).

The Hercynian history was closed by folding associated with emplacement of numerous plutons and extensive

regional metamorphism. This folding had reworked the whole region and often obscured the earlier, Cadomian and probably also some Caledonian structural elements. From this point of view, the Bohemian Massif has a tripartite structure consisting of the following vertical groups:

- Precambrian (Cadomian) basement;
- Crystalline and Paleozoic affected by Hercynian orogeny; and
- Post-Hercynian platform cover.

8.7.2 Basic geological requirements for host rock

The basic requirements for the geological unit that should become a host structure for DGR can be defined as follows:

- sufficient area (tens of square km) and thickness (at least 1000 m);
- lithological homogeneity of the unit with minimal hydrothermal alterations and rock veins;
- tectonic fractures and displacement as low as possible;
- no deposits and indications of mineral resources;
- permeability as low as possible; and
- seismic and geodynamic stability of the region.

8.7.3 Geological units of the Bohemian Massif from standpoint of basic requirements for host rock

Individual geological units can be evaluated from the point of view of suitability for DGR siting as follows:

Post-Hercynian platform cover. Post-Hercynian platform cover on the territory of the Czech Republic can be divided according to age into:

- Permo-Carboniferous sediments;
- Mesozoic sediments; and
- Tertiary sediments.

Permo-Carboniferous sediments occur in the territory of the Czech Republic in two different forms. In the north-east part of the Czech Republic, only a basin is situated where the parallel Namurian developed gradually from the marine Lower Carboniferous. In other parts of the Czech Republic, there are numerous limnic Permo-Carboniferous sediments placed discordantly upon various older units. We regard Permo-Carboniferous sediments as unsuitable for DGR because of their litholog-

ical variety and relatively extensive tectonic displacement.

The absolute majority of Mesozoic sediments in the territory of the Czech Republic are of Upper Cretaceous age. Continental sediments of Lower Triassic and epicontinental sediments of Upper Jurassic have no significance because of their small range. Lacustrine sediments of the Upper Cretaceous are known in the southern part of the Czech Republic, where they filled two separate basins. As far as their lithological nature is concerned, they are composed of sandstones, siltstones and claystones with rapid vertical as well as horizontal changes. In the north of the Czech Republic the Bohemian Cretaceous Basin is widespread. Its area is approximately 14,000 km². The largest supply of high quality drinking water in the Czech Republic is found in sandstones. Mesozoic sediments are regarded as unsuitable for DGR because of their lithological nature.

The majority of Tertiary sediments is mostly of lacustrine origin. They occur, on the one hand, in the northwest of the Czech Republic (accompanied by alkaline volcanism of Tertiary and Quaternary age), where they form the filling of the vast, tectonically predisposed, system of basins, and, on the other hand, in the south of the Czech Republic, forming the overlying beds of Upper Cretaceous sediments. As far as their lithology is concerned, they are characterized by rapid horizontal, as well as vertical, changing of clays and sands. In the northwest there are important and intensively exploited lignite seams, which are part of these sediments.

As far as the DGR is concerned, the Tertiary sediments do not have desirable features, especially because of their lithological variety and significant tectonic fractures.

Crystalline and Paleozoic affected by Hercynian orogeny. This group includes metamorphosed pre-Cambrian and Paleozoic rocks and non-metamorphosed rocks of Lower Paleozoic (Cambrian to Middle Devonian). Cadomian and Hercynian plutonic rocks are numerous.

Non-metamorphosed Cambrian to Middle Devonian formations occur in several separated basins. The formations in question are predominantly shales, siltstones, carbonates, sandstones and conglomerates, often accompanied by volcanism. In our opinion these formations are not suitable for DGR siting, because of their intensive folding, tectonic displacement and in view of

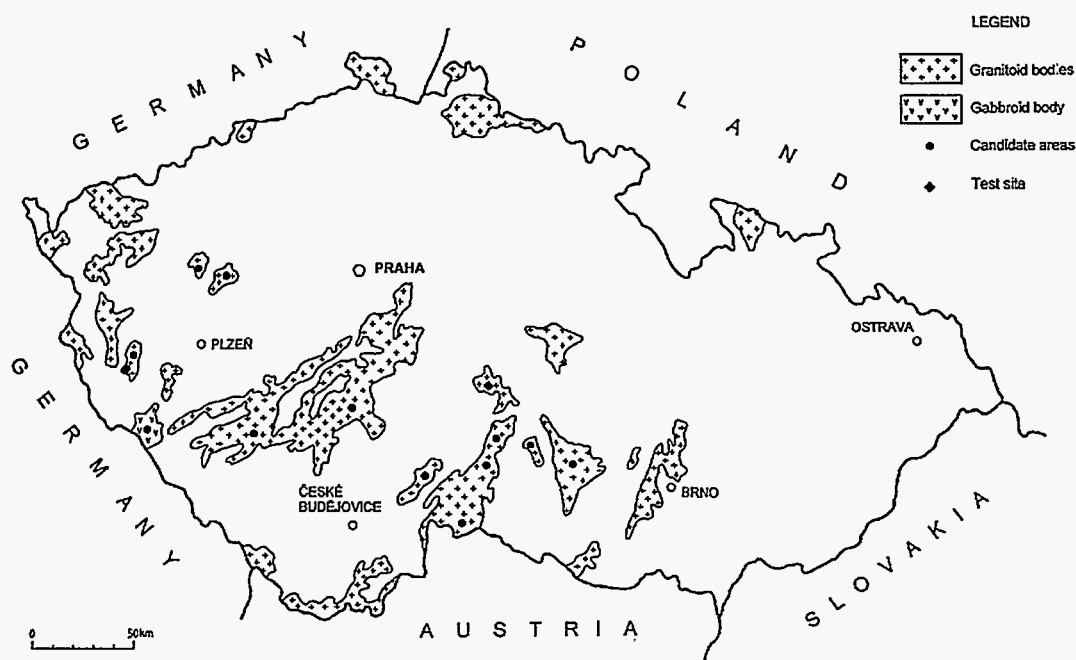


Figure 8.2. Location of candidate areas and test site in the Czech Republic.

varied lithological composition and karstification of limestones.

Units of metamorphosed rocks prevail in this group. Elements of Cadomian metamorphism appear in most of these units. According to geological and geochronological data, the Cadomian metamorphic activity can be observed from 650 to 550 Ma. Presence and role of the Caledonian metamorphism is still discussed by experts. The Hercynian regional metamorphism is most significant in the territory of the Bohemian Massif. This metamorphism started in the Ordovician, culminated in the Upper Devonian and ended in the Carboniferous.

In view of the very complicated tectonic structure, often and rapidly changing intensity of metamorphosis and lithological variety of metamorphosed units, where moreover numerous intercalations of crystalline limestones, graphite layers or quartz veins occur, we do not regard the metamorphosed units as suitable host rocks for DGR.

The occurrence of extensive plutonism is a characteristic feature of the above mentioned group (Fig. 8.2). The following plutonic complexes have been distinguished:

- metaplutonites of uncertain age, which occur predominantly in the form of orthogenesis in marginal

parts of the Bohemian Massif;

- plutonites associated with Cadomian orogeny, which form several granitoid and gabbroid bodies in the west and north parts of the Czech Republic; and
- plutonites associated with Hercynian orogeny, which are the most frequent on the territory of the Bohemian Massif.

The Hercynian plutonites are exclusively granitoids. The two largest bodies - the Moldanubian Pluton with area of 8,000 square km approximately, and the Central Bohemian Pluton with the area of 3,200 square km approximately, as well as many smaller bodies belong among them. According to geochronological data, the age of the majority of the above mentioned granitoids is between 350 - 300 Ma, and their development is connected to the late tectonic phase of Hercynian metamorphic stage.

We consider granitoid bodies connected with the Cadomian as well as Hercynian orogeny as suitable for DGR.

Precambrian (Cadomian) basement. Precambrian basement untouched by the earlier Hercynian orogeny occurs in the territory of the Czech Republic just in Brunovistulicum. This unit as a whole is not suitable for DGR location especially because of its significant geo-

logical variety.

8.7.4 Description of General Project Objectives

The present state of activities on DGR siting in the Czech Republic results from work which was performed during the last 5 years. An area selection of 27 suitable regions was performed on the basis of existing regional geological information by the Czech Geological Survey.

The siting process continues with the approval of the General Project of Geological Activities for Deep Geological Repository Siting, which was elaborated by NRI staff. The project cut the number of potential areas from 27 to 13. From this number, 12 areas are located in granitoid bodies and one in an ultrabasic body. The area of relevant sites ranges from 120 to 20 square km.

The General Project became a principal document, upon which all geological activities concerning development of the deep geological repository are performed. Principal geological activities are planned in accordance with the General Project for approximately the following 15 years. It is assumed that the deep geological repository will be put into operation in 2035.

The activities described in the project are divided into the following stages:

- research activities;
- seismicity, geodynamics and neotectonic monitoring;
- critical evaluation of pre-existing geological information;
- site characterization; and
- site confirmation.

The project does not deal in details, neither with an underground laboratory nor natural analogues. These activities are supposed to be solved by independent projects, whose time schedule and logical structure will be co-ordinated with the General Project, especially with the stage of research activities.

Stage of research activities. The main task of this stage is development, practical verification and elaboration of obligatory methodological procedures relevant to the deep geological repository siting. These activities will be performed at the test site selected in geological conditions similar to those, where the construction of the repository is proposed. The site in question is Moldanubian Pluton apophyse. DGR will not be built at the testing site, but we will consider the siting of an underground laboratory there. Currently, characteriza-

tion of the site is being performed. The project of research activities will be completed in 1997, and the activities are supposed to start in the same year.

Stage of seismicity, geodynamics and neotectonics monitoring. In view of the above mentioned geological structure of the Bohemian Massif and its incorporation in the European Hercynides, no significant motions can be expected, but on the other hand insignificant motions cannot be excluded with sufficient certainty. However insignificant the motions might be, they could negatively influence the DGR safety. That is why we pay the necessary attention to monitoring the stability of the relevant part of the Bohemian Massif.

These activities will be started at the end of 1996 or in the beginning of 1997. In a preparatory phase, all available information on hardware and software concerning scanning data and their transmission to the processing center as well as their processing and evaluation will be gathered. Simultaneously, selection of suitable posts for seismometers, determination of sites suitable for neotectonic studies, densification of the network of existing observing points will be realized. The remote sensing evaluation will also be realized within this stage.

Stages of critical evaluation of pre-existing geological information, site characterization and site confirmation. These stages represented activities, which will result in selection of the optimal site for DGR in the territory of the Czech Republic. The activities began in 1995 and at present, a critical evaluation of available geological information is in progress. Starts of the next two stages are scheduled for 1998 and 2003. Contents of the single above mentioned stages are as follows:

The stage of **critical evaluation** of pre-existing geological information includes collecting of geological data from archives. The principal evaluating criterion is the nature and quality of each information and its utilization for siting. The data being evaluated concern geology, geophysics, hydrogeology, hydrology, climatology, geochemistry, seismology, but also demography, environmental protection and the most significant conflicts of interests. Approximately 7 sites are supposed to be selected from existing 13 at the end of this stage and recommended for the next stages.

Within the **site characterization** stage, a non-destructive (not disturbing rocks in the depth, where DGR might be situated) geological survey will be performed at all sites. This stage will include:

- geological mapping at a scale of 1 : 10,000 and structural geology studies;
- aerial and surface geophysics, especially gravity measurement, magnetometry, geoelectric methods, logging measurements in all bore holes and other necessary methods;
- boring works down to a depth of 200 - 300 m;
- detailed petrologic and mineralogic studies;
- geochemical mapping;
- hydrological and hydrogeological characterization of the site; and
- engineering-geological mapping and geotechnical characterization of the site.

These activities are supposed to be performed on sites with an area of 10 - 50 square km each. In addition, the granitoid body surrounding metamorphosed complexes will be examined to the necessary extent in justified cases.

A detailed descriptive characterization of the whole territory will result from this phase. On the basis of this characterization, a final decision on the suitability of the examined site, or its part for DGR siting, will be made. This stage results in a selection of two or three sites for further investigation.

The **site confirmation** stage. Destructive phase of activities will be started in one of the candidate sites, the others will serve as spare ones. Boring and special geophysical methods will be used predominantly in this stage. According to the assumptions of the General Project, the details of the verified site for DGR construction in the Czech Republic should be known by 2010.

8.8 CONCLUSIONS

Disposal of radioactive wastes has been practiced in the Czech Republic for more than 40 years. Different geologic environments were selected as host rocks for those subsurface facilities. This experience allows us to carry out successful research and development of a deep geological repository able to accept both decommissioning long lived and/or high level wastes and spent fuel from nuclear reactors. When considering the available geological systems and its variability in the Czech Republic, hard rocks, namely granitoid bodies, seem to

be the most hopeful rocks for construction of a deep geological repository. The relevant national program was initiated in the early nineties aimed at development of this underground facility.

Technical abilities, however, are not fully supported by existing legal tools and the organizational system. Parallel management of radioactive wastes arising from different sources will probably survive till the newly prepared Atomic Law passes through the Czech parliament. In dealing with radioactive waste management, the governmental proposal contains several new principles, namely:

- state guarantees safe disposal of radioactive wastes, although the waste generators must bear the respective costs;
- import of radioactive wastes for their disposal on the Czech territory is forbidden;
- Nuclear Account, established out of the state budget, collects fees from waste producers to ascertain enough financial sources for final disposal of all radioactive wastes; the Account is controlled by a committee consisting of representatives of waste producers, state institutions and public; and it is under the supervision of the Ministry of Finance;
- new Office of Repository Management is created; it provides disposal services in existing facilities and is responsible for research and development in this field, including development of a deep geological repository; and
- a position of the State Office for Nuclear Safety as an independent supervisor in nuclear and radiological issues is stressed.

The Atomic Law shall be completed with a set of nearly 20 decrees providing the concrete regulations for users of radionuclides.

Even if the existing legislation is updated, siting of nuclear facilities, such as storage and disposal facilities, will have to face the high population density in the Czech Republic (130 inhabitants per square km) and all the negative consequences that this fact may imply. Nevertheless, it is believed that all kinds of radioactive wastes and spent nuclear fuel will be safely conditioned and disposed of in the Czech Republic.

CHAPTER 9

DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE IN FINLAND

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Abstract. Detailed site investigations are under way on three candidate sites with the aim of selecting the site for a final repository for spent fuel in 2000. In May 1995, the Finnish nuclear power companies, IVO and TVO, made an agreement on the establishment of a joint company for final disposal of spent fuel in Finland, and the new company, Posiva, has taken over the work so far conducted solely by TVO for the disposal of spent fuel. After site selection, the first exploratory shaft will be constructed on the nominated site, and the actual construction of the repository will be started in the 2010's. According to the time schedule set by the Finnish Government in 1983, the repository must be available in 2020.

9.1 INTRODUCTION

About one third of the electricity produced in Finland is currently generated by nuclear power plants. There are two pressurized water reactors (PWR) with a combined capacity of 890 MWe at Loviisa and two boiling water reactors (BWR) with a combined capacity of 1420 MWe at Olkiluoto. The PWR power plant is owned and operated by Imatran Voima Oy (IVO), the BWR plant, by Teollisuuden Voima Oy (TVO).

According to Finnish legislation the nuclear power producer is solely responsible for the management and disposal of all radioactive wastes, including the spent fuel. Funds for future waste handling and disposal are included in the price of electricity and are set aside in a special fund under the authority of the Ministry of Trade and Industry (KTM). The Government has set the basic guidelines for waste management in a resolution of 1983 concerning the goals for research and planning in the area. These guidelines have been further focused and updated by decisions of KTM. In these guidelines and decisions, time schedules are set for construction of the final disposal facilities, and, in addition, some general principles are given for the research and development (R&D) programme.

The Loviisa power plant units are based on the Russian VVER-440 design and, in connection with the purchase of the reactors, the utility also made contractual arrangements for the entire fuel cycle service from the former USSR. This included both the supply of fresh fuel and

the return of spent fuel back to the supplier. After the break-up of the USSR, the contract was endorsed by the Russian Government and the return shipments of spent fuel continued on a regular basis.

In late 1994, however, the Finnish Parliament passed an amendment to the Nuclear Energy Act which prohibits all exports and imports of nuclear waste, including spent fuel. A two-year transition period was granted for IVO's shipments of spent fuel to Russia, but from 1997 on, the spent fuel from Loviisa nuclear power station will be retained for final disposal in Finland.

In view of this new situation, the two nuclear power companies, IVO and TVO, started discussions on cooperation for a common disposal facility for their spent fuel. The companies already coordinated their nuclear waste research through the Nuclear Waste Commission of the Finnish Power Companies (YJT), and the question was how this cooperation could be enhanced in a joint undertaking.

These discussions were concluded in May 1995 in an agreement on the establishment of a joint company for the final disposal of spent fuel in Finland. From the beginning of 1996, the new company, Posiva, takes care of all the planning, research and development work needed and will later construct and operate the encapsulation facility and the deep underground repository. The mission neither includes interim storage of spent fuel nor the disposal of low- and intermediate-level operating wastes, for which the two power companies will

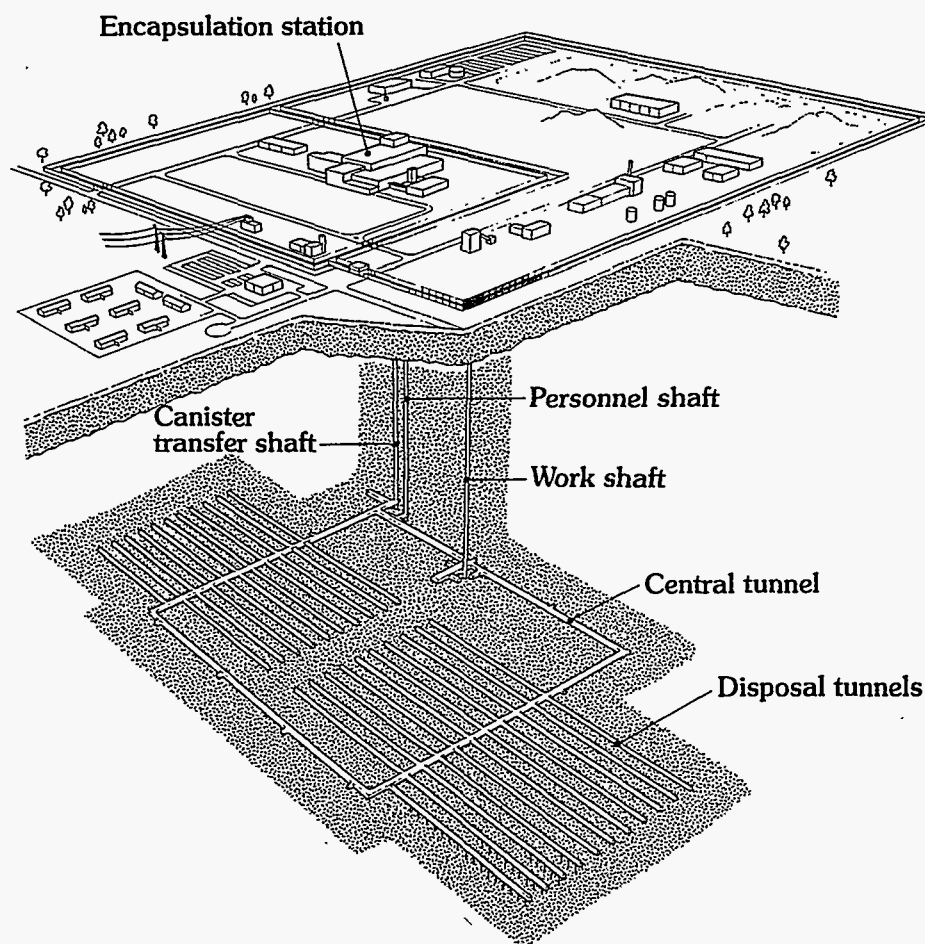


Figure 9.1. Final disposal facility for spent fuel.

have separate disposal facilities; TVO has had a repository in operation since 1992, and IVO has a repository under construction.

The programme for the final disposal of spent fuel will proceed along the time schedules originally set by the Government for the disposal of spent fuel from the TVO power plant. The plan is to dispose of the spent fuel directly, without reprocessing. According to the time schedule, the final repository for spent fuel must be available in 2020, and the site for the repository has to be selected by the end of the year 2000. Accordingly, the construction of the repository will be started in the 2010's. The total amount of spent fuel to be disposed of in the repository will be about 2500 tHM.

9.2 PROGRAMME STATUS

The technical plan for final disposal is based on the KBS-3 concept¹, but a new design for canisters has been

introduced by TVO. Complete technical plans for disposal, together with a safety assessment, were submitted to the authorities at the end of 1992².

The concept consists of emplacing the packaged spent fuel in vertical holes in tunnels that have been excavated deep in the bedrock (Fig. 9.1). The repository depth will be somewhere between 300 m and 800 m depending on the geology and other characteristics of the site and also on various safety-related considerations. Fig. 9.1 depicts an idealized situation; in practice the tunnel network will be adapted to local bedrock features and may be split in several parts to avoid crossing major fracture zones. The packaging of the waste will take place at an encapsulation plant which will be constructed at the repository site at the surface. An elevator can then be used to transfer the waste packages directly to the repository.

In the new canister concept, the "Advanced Cold Pro-

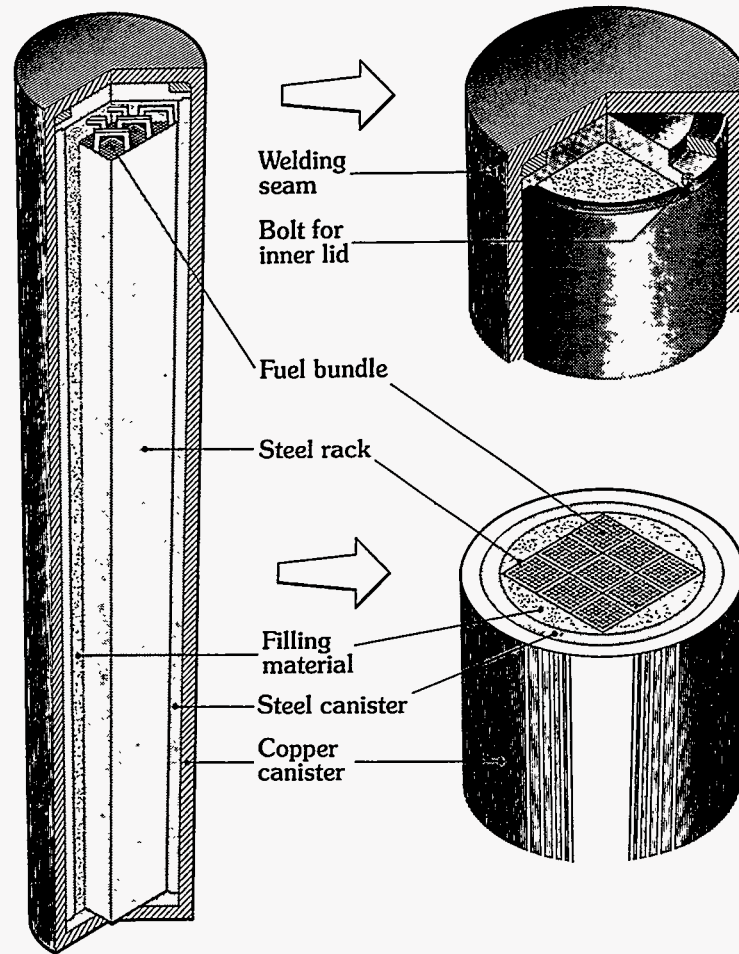


Figure 9.2. Advanced cold process (ACP) canister for direct disposal of spent fuel.

cess" (ACP) canister is a composite canister consisting of an inner container of steel as a load-bearing element and an outer container of oxygen-free copper to provide a shield against corrosion (Fig. 9.2). The wall thicknesses are 60 mm for the copper canister and 55 mm for the steel canister. The original canister design was only for 9 BWR fuel assemblies from the TVO power plant, but it has been modified for the hexagonal fuel elements from the Loviisa PWRs assemblies as well. The empty space in the canister can be filled with a granular material, such as lead shot, glass beads or quartz sand, but other alternatives are also being considered. Depending on the filling material used, the total weight of the full canister will be 14 to 20 tonnes.

The name of the canister design (Advanced Cold Process Canister) is due to the principal driving force behind the development work. The original KBS copper canister design assumes a lead casting to fill the voids between the fuel assemblies and canister walls. Since

the lead casting would probably be the technically most difficult phase in the encapsulation process, the question was raised whether the use of molten lead could be avoided by replacing it with some "cold" material. However, the copper canister without the cast lead might not meet the mechanical requirements, mainly because of the creep properties of copper. In the ACP canister, the use of molten lead has been avoided because the mechanical strength is now provided by the inner steel canister.

For the selection of the repository site, the strategy is to find a "good enough" site, i.e., a site that offers sufficient characteristics to ensure the long-term safety of disposal. It is considered both unnecessary and unrealistic to try searching for the "best" site.

The site selection process for a repository started in 1983 with a country-wide survey of the principal geological features in Finland. The approach used for local-

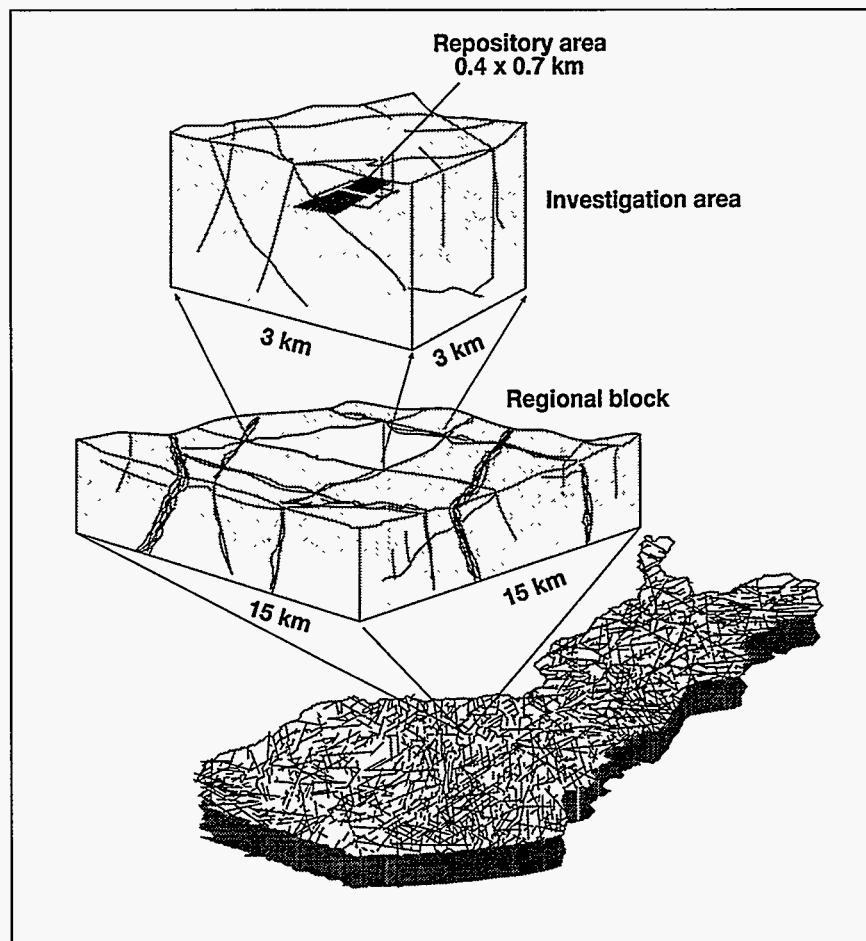


Figure 9.3. Principle site selection for the spent fuel repository.

ization of candidate sites was based on the crush-tectonic block structure of the Finnish bedrock. All the bedrock in Finland is broken down into blocks separated by regional crush (or shear) zones whose length may be dozens of kilometres (Fig. 9.3). These, in turn, are divided into smaller sectors according to the presence of smaller fracture zones. What is important for repository siting is that the rock response to future changes in stress conditions be mainly confined to these crush zones, while the rock outside the fracture zones remains basically unaffected. This will ensure sufficient stability for the host rock of the repository.

A total of 327 large regional blocks were identified in the first country-wide screening of the bedrock features. Mainly for land-use restrictions and other geographic reasons, the number of possible regions was later reduced to 61, among which 134 smaller areas were selected as candidates for investigation sites. In 1987,

five areas were selected for preliminary site investigations. These are situated in different parts of the country and represent somewhat different geologic histories (Fig. 9.4). In addition to geologic factors, geographic factors, land ownership and transport and other infrastructure considerations were taken into account in the selection of the sites for preliminary site investigations. One of the areas chosen for investigations is the Olkiluoto island in Eurajoki where the TVO power plant is also situated.

The principal goal of the preliminary site investigations was to characterise the candidate sites to the extent needed to judge whether the preconception on their suitability for hosting a repository could be confirmed. The investigations at each site comprised drillings and samplings, various geophysical, geohydraulic, rock-mechanical, chemical and mineralogical studies, and modelling of the bedrock structure and groundwater

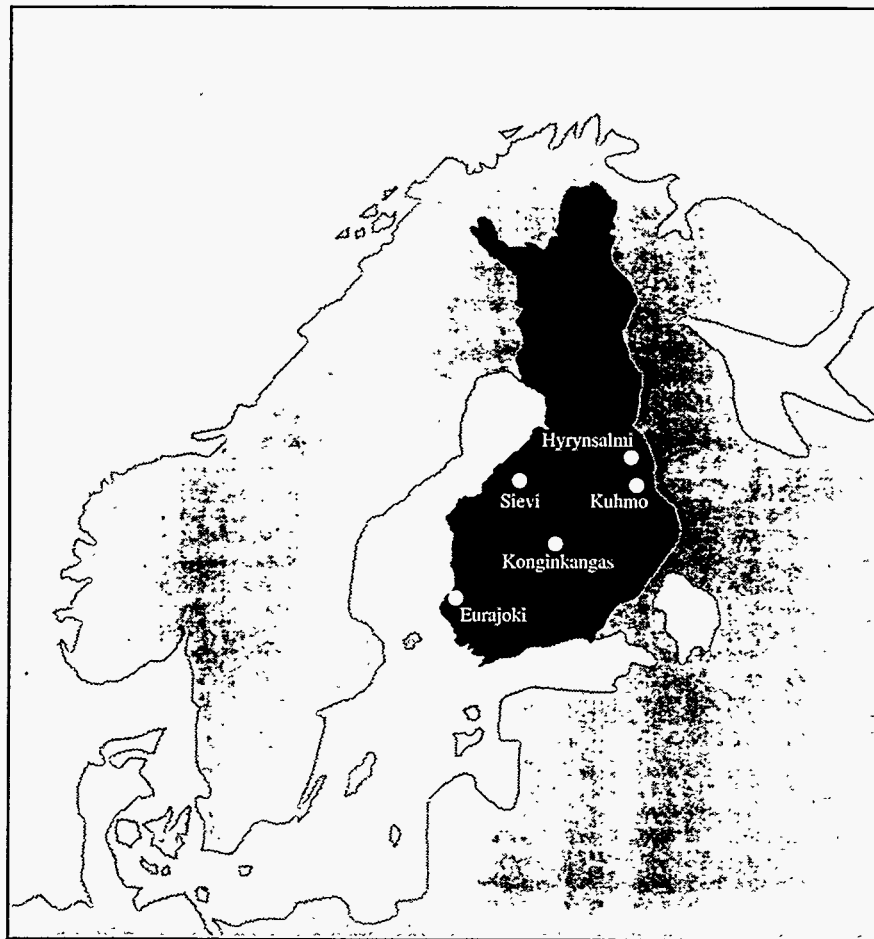


Figure 9.4. Preliminary site investigations areas in 1987-1992. Kuhmo, Konginkangas (since 1993 a part of Aankoski town) and Eurajoki were selected in 1992 for detailed site investigations.

flow in the area. At least five deep (500 to 1000 m) cored boreholes were drilled in addition to a number of shallow boreholes. The results of the preliminary site investigations were submitted to the authorities at the end of 1992³. These results did not reveal any surprises in relation to expectations; no exceptional features were detected that would compromise the siting of the repository within the area studied.

In parallel with these site investigations, a safety assessment ("TVO-92") was carried out⁴. The analysis used the data from the preliminary site investigations but was not specific as to any of the sites studied. The principle has been to select the parameters and assumptions in such a way that a location could be found at each of the sites with certainly more favourable conditions than were assumed in the safety assessment. For example, very conservative assumptions were made with regard to groundwater flow at the repository site. It was assumed

in the reference scenario of the analysis that the groundwater transit time from the repository to the biosphere is only five years.

The safety analysis includes a detailed groundwater flow analysis for a hypothetical repository located at one of the investigation sites. Figure 9.5 depicts how the repository could be adapted to the local fracture zones around the deep drillholes. It is seen that two fracture zones, R11 and R15, cross the repository area. If the transmissivity of the repository (together with the excavation damage zones) were high in relation to the surrounding rock, then in principle, a U-tube flow condition could form. Although, in reality, this would be very unlikely, such a situation has been taken as the basis in the reference scenario of the safety assessment.

The number of scenarios was kept small by restricting the analysis to a set of bounding cases that, nevertheless,

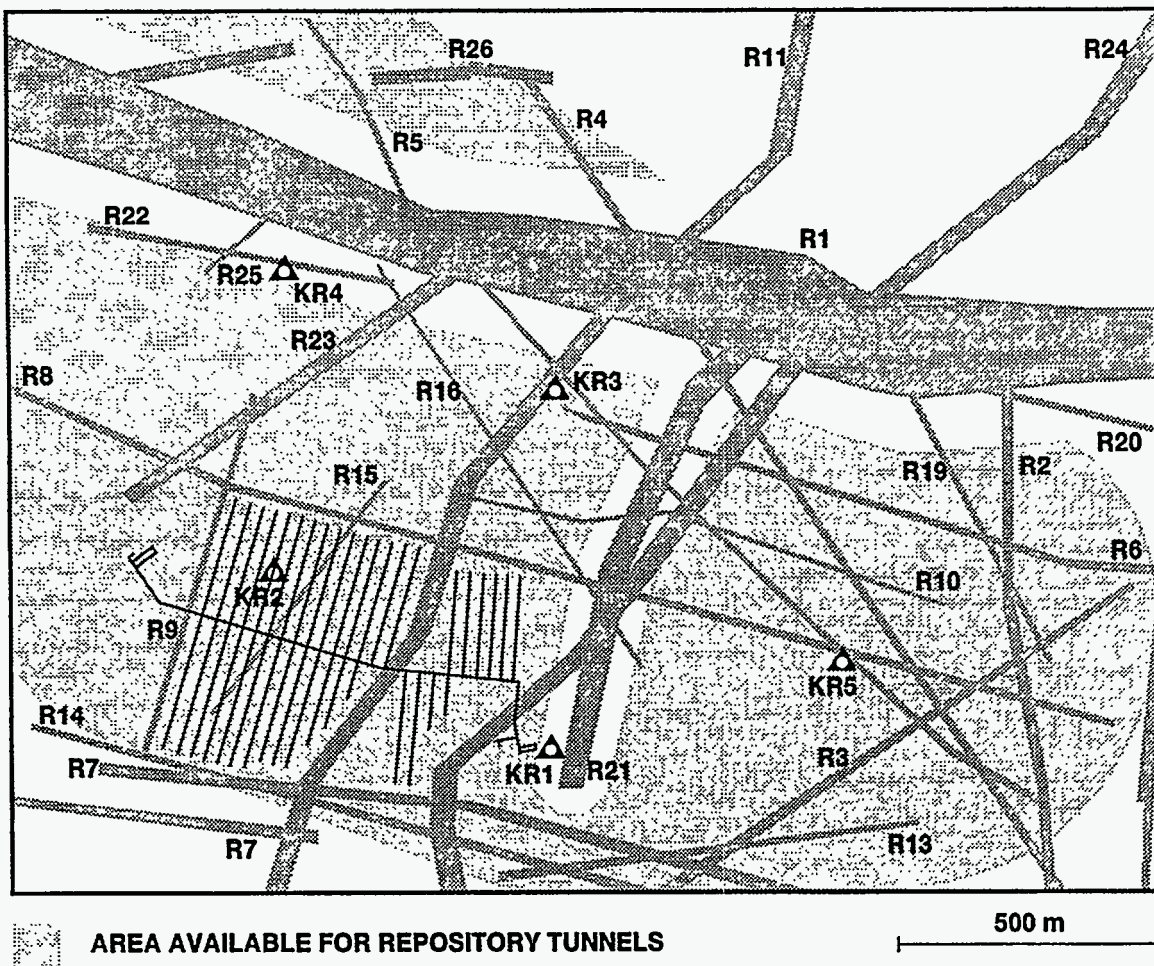


Figure 9.5. Adaptation of the repository to local bedrock features (example from Hyrynsalmi investigation site).

cover all reasonably conceivable situations. Aside from the base case (the conditions in the vicinity of the repository remain basically as they are now), the analysis has been centred on the reference case, which simply assumes a total loss of canisters after 10,000 years from the time of deposition. This simplification has helped to greatly reduce the number of different scenarios in the analysis.

Despite the conservative data and concepts adopted, the safety analysis shows that the criteria proposed by the Nordic safety authorities in 1993 can easily be met⁵. At the same time, the analysis shows that safety is ensured no matter which one of the candidate sites is chosen.

In addition to geology and long-term safety, various other aspects of the candidate sites were assessed, such as local infrastructure and available means and routes of transportation and constructability. It turned out that

there were no decisive differences between the sites studied. However, for focusing the field work further, the decision was made to restrict the detailed investigations to three candidate sites: Eurajoki, Kuhmo and Äänekoski (formerly Konginkangas). The choice was mainly based on the practicality of investigations; it was evident that at the two discarded sites (Sievi, Hyrynsalmi), investigations would have to be extended over a larger area than was well covered by the drillings during the preliminary site investigations. At the three selected sites, the future investigations could most efficiently make use of the already existing boreholes and other data.

9.3 FUTURE INVESTIGATIONS

Detailed site investigations are now under way on the three candidate sites with the objective of establishing the database needed for site selection in the year 2000.

In 1994, TVO also conducted a prefeasibility study in Kannonkoski, a neighbouring municipality to Äänekoski, as a possible site for the repository. On the basis of a geologic survey and other considerations, it was concluded that Kannonkoski could be an alternative to Äänekoski, in case there was need to search for new candidate sites; but for the moment, the three candidate sites are considered sufficient. Now, after the decision by IVO and TVO to work toward a joint repository, a similar prefeasibility study is being conducted at Loviisa, the site of the IVO power plant. The need for drilling and other field work at Kannonkoski or Loviisa will be considered at the end of 1996, when an interim report of all studies and investigations conducted since 1992 will be submitted to authorities.

For site selection, a site-specific safety analysis will be carried out for the nominated site and the technical concept by the end of 2000. Updated technical plans will be presented, including preliminary layouts adapted to the local geologic features. Later, in the early 2000's the first exploratory shaft will be constructed at the site, and the construction work for the repository itself can be started after 2010, assuming a favorable development with the licensing.

For drilling and other surface-based site investigations, the only license required so far is permission from the land-owner, who, in the case of the candidate sites, is the state or the power companies themselves. However, construction of the repository is possible only after a positive decision by the Parliament, and such decision can only be made if the local municipality approves the siting proposal. Since the local veto cannot be overrid-

den, public acceptance will be crucial for the successful implementation of the plans. According to the present time schedule, the municipality will have to define its position on the proposed siting in about ten years. To gain local support for the plan will be a major challenge in providing for the ultimate disposal of nuclear wastes in Finland.

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