Safe, Permanent Disposal of Nuclear Fuel Waste

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Abstract
This paper describes the Canadian concept for safe, permanent disposal of nuclear fuel waste deep in plutonic rock of the Canadian Shield. The ability of the disposal concept to isolate the wastes is then discussed in the light of laboratory and field research results. The methodlogy developed to characterize the hydrogeology of a plutonic rock mass is outlined and results obtained from its application to a field site are described. Also highlighted are the Canadian field research areas and the Underground Research Laboratory.

Résumé
Dans la présente communication, on décrit le concept canadien d'évacuation sûre, permanente, des déchets de combustible nucléaire à grande profondeur dans la roche plutonique du bouclier canadien. Ensuite on examine la capacité du concept d'évacuation d'isoler les déchets à la lumière des résultats de recherche en laboratoire et sur le terrain. On donne un aperçu de la méthodologie développée pour caractériser l'hydrogéologie d'une masse rocheuse plutonique ainsi que le détail des résultats obtenus en l'appliquant à une zone de recherches sur le terrain. En outre, on met en lumière les zones de recherches sur le terrain au Canada et le Laboratoire de Recherches Souterrain.

Introduction

Nuclear fuel wastes have been managed safely in Canada since the mid-1940's, when the first wastes were produced: first, at the Chalk River Nuclear Laboratories and, more recently, at each of the nuclear-electric generating stations. The waste producers recognized from the beginning that permanent disposal would be necessary as the final management step.

In the mid-1970's, Energy, Mines and Resources Canada initiated a study, led by Professor F.K. Hare of the University of Toronto, to identify disposal methods suitable for implementation in Canada. The study concluded [Aitken *et al.* 1977]:

1 Underground disposal in geologic formations was the most promising option within Canada and igneous rocks were the preferred geologic medium.
2 The repository should be regarded as a central, national facility and should be located in Ontario.

Surface disposal was rejected because it would leave to future generations the duty to keep watch on the wastes, and would be more vulnerable to man-made hazards. It was accepted that if something should go wrong with a deep geological disposal site, it would be difficult to rectify; nevertheless, if done correctly, such disposals could be forgotten by future societies.

Based on the recommendations of the Hare Study, the Governments of Canada and Ontario, in 1978, launched the Nuclear Fuel Waste Management Program. AECL was given the responsibility for assessing the concept of disposal of nuclear fuel wastes deep in plutonic rock of the Canadian Shield, and for developing and demonstrating the associated technologies [Boulton 1978]. It was recognized that the physical and chemical processes that might lead to release of radioactive materials and to their transport back to the surface would evolve over thousands of years. Therefore, it would not be possible to provide a direct physical demonstration of the concept's safety. The approach adopted was to base the demonstration of safety on long-term predictions using mathematical models that represent the various components of the disposal system, including the waste material and the plutonic rock mass. The research program was designed to provide a thorough understanding of the underlying physical and chemical processes, to develop appropriate models, and to validate them against carefully integrated laboratory and field experiments.

The research program is now well advanced and a comprehensive understanding of the waste isolation

Keywords: geologic disposal nuclear fuel waste.

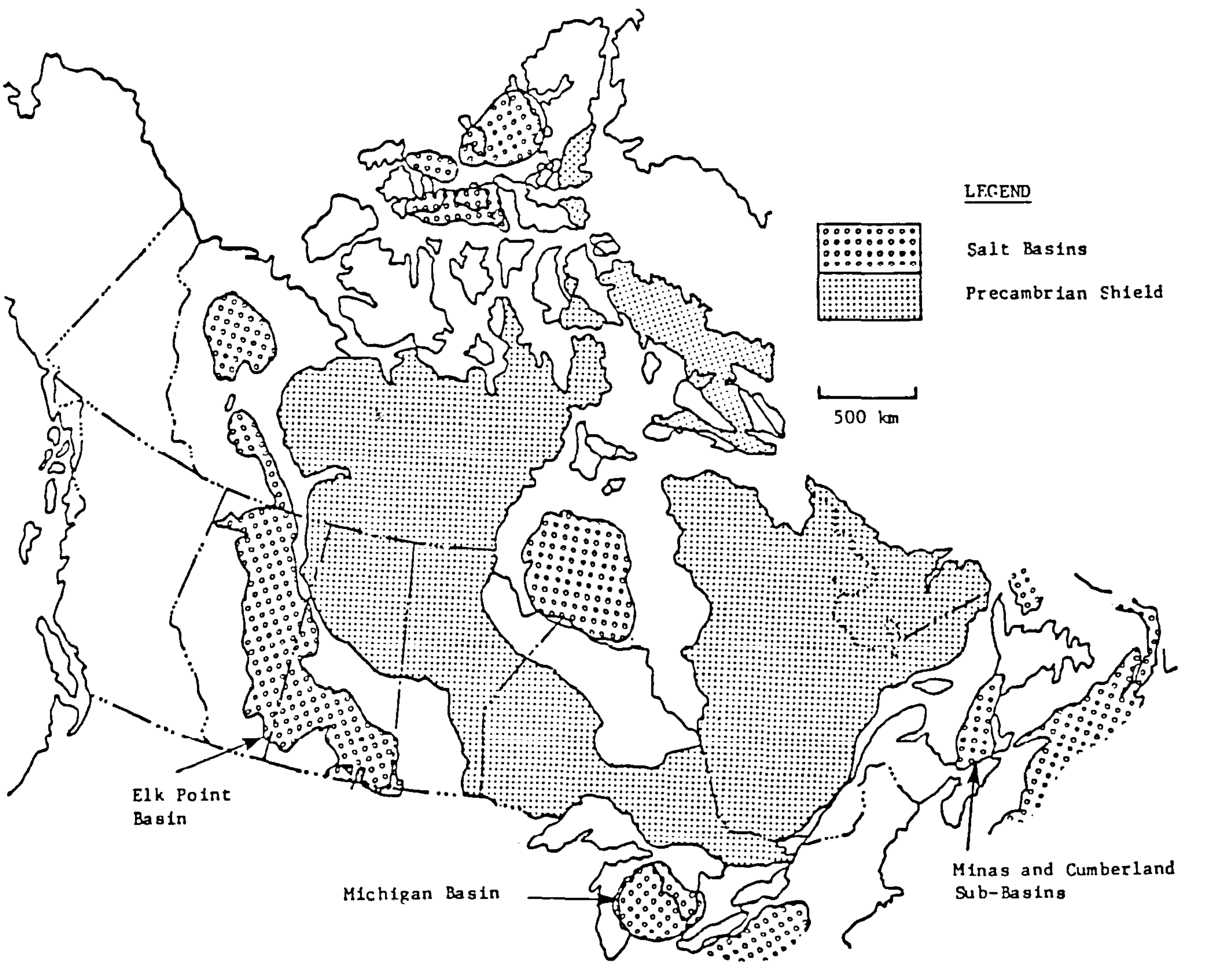

Figure 1 Some geological formations in Canada of potential interest for nuclear fuel waste disposal.

capability of the concept has evolved [Hancox 1986]. In the light of this understanding, a review follows of the rationale for the choice of plutonic rock as the disposal medium. Next, the nature of nuclear fuel waste, the concept for its isolation, and our current understanding of physical and chemical processes that ensure isolation, are outlined. Then, field research areas are highlighted that have contributed to our understanding of groundwater flow systems and geochemical processes, and to the development of our methodology for characterizing the hydrogeology of candidate disposal sites. Finally, the Underground Research Laboratory is described.

Geologic Medium

The concept of using a multi-barrier system involving a geologic medium in combination with engineered systems has gained strong technical support as the most feasible method for nuclear fuel waste disposal [OECD 1986]. There are a variety of potentially suitable geologic media, such as plutonic rock, bedded salt, and volcanic tuff, all of which can, under the right conditions, provide an acceptably safe site for a disposal vault. Where countries are studying more than one geologic medium, the rationale is to ensure that there are a number of locations, with a wide geographic distribution, available for selecting an acceptable site. Some countries have already selected the geologic medium that makes most sense for them: for example, salt in Germany, clay in Belgium, and plutonic rock in Canada and Sweden.

The defining criteria for appropriate geologic media include:

1 many potential sites in the geographic region of interest;
2 geologic stability for hundreds of thousands of years, and freedom from economically attractive concentrations of minerals, making future subsurface exploration unlikely;
3 groundwater transport times of hundreds of thousands of years from deep in the rock mass to the surface; and
4 geologic and hydrogeologic characteristics that can be readily determined using available technology, and that lend themselves to mathematical description.

Figure 1 shows geologic formations in Canada with

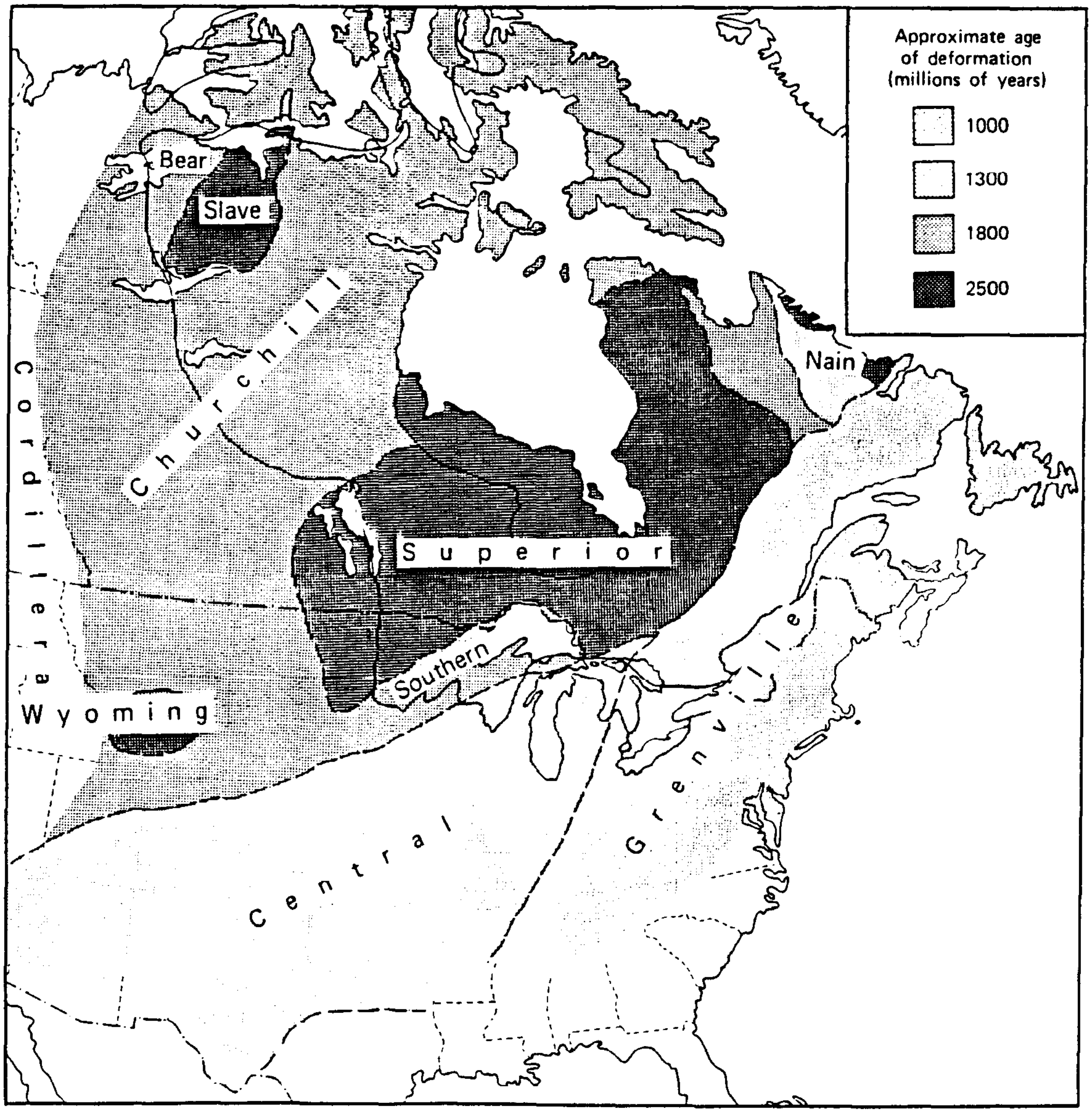

Figure 2 Structural Provinces of the Canadian Shield. (From *Stern CW, Carroll RL, Clark TH.* Geological evolution of North America. 3rd. ed., John Wiley & Sons, 1979.)

attributes of potential interest for nuclear fuel waste disposal [Mayman *et al.* 1976], salt basins, and the Precambrian Shield. Most of the salt basins are located outside the provinces with established nuclear power programs, and most coincide with petroleum and potash production activities. As a result, selection of salt as a disposal medium would severely limit both the geographic location of a site and the number of potential sites.

Figure 2 shows the structural provinces of the Precambrian Shield. In contrast to the relatively limited geographic distribution of salt, plutonic rocks of the Superior structural province of the Precambrian Shield are predominant over much of the province of Ontario, where the majority of Canada's nuclear power plants are located. Further, plutonic rocks of the other structural provinces extend beneath sedimentary rocks over much of North America. Selection of plutonic rock as a disposal medium provides a wide range of potential geographic locations and a large number of potential sites.

The Canadian Shield has been relatively stable for at least 600 million years, and most of the Shield has not had major orogenic activity for 2.5 billion years. Therefore, it is not a large extrapolation to infer that the region will remain stable for the required lifetime of a disposal vault. Also, regional topographic gradients in the Shield are low, about 1 m / km. As a result, the natural driving force for groundwater flow deep in the rock should be weak. Further, field investigations indicate that there are large plutonic rock masses with extremely low porosity and permeability. These would serve to limit access of groundwater to the waste, thereby slowing its deterioration and inhibiting movement of radionuclides through the rock. Also, minerals in plutonic rock are known to react with many of the radionuclides in nuclear fuel waste, further retarding their movement.

The broad classification of plutonic rock includes all rocks crystallized from a molten state deep within the earth's crust. Large individual intrusives, known as plutons, have been the main focus of our research, because these bodies tend to be of relatively uniform composition and high structural integrity. These plutons fall within the mineralogical spectrum that ranges from granites, relatively high in quartz and feldspar, to gabbros, relatively enriched in minerals containing magnesium and iron. Therefore, we decided to study both granitic and gabbroic plutons. However, it should be emphasized that our field research has not been confined to plutons, but has included the metamorphic rocks into which they have intruded.

To determine the acceptability of a disposal concept, the following are required:

1 criteria that define what is acceptably safe;
2 methodology to evaluate proposed disposal systems against the safety criteria;
3 technology to site and build a disposal vault that satisfies the safety criteria;
4 confidence that an acceptable site can be found.

The criteria that define an acceptably safe disposal system are the responsibility of regulatory and environmental agencies. The basic criteria to be adopted in Canada for the long-term management of radioactive wastes have recently been issued by the Atomic Energy Control Board [Atomic Energy Control Board 1984 and 1986]. These criteria are independent of the geologic medium chosen.

The methodology to assess the performance of a proposed disposal system against the basic safety criteria is being developed and validated as part of our research program, and consists of an integrated program of laboratory and field analysis, engineering design, and mathematical modelling. Although some details are specific to plutonic rock, the methodology itself can be adapted to any geologic medium.

The technology to site and construct a disposal system is the most dependent on the geologic medium. In our program, technology has been developed to:

1 determine geological and hydrogeological characteristics of plutonic rock masses to depths up to 1000 m;
2 determine the thermal-mechanical response of a rock mass to the excavation of a disposal vault and to the heat produced by emplaced fuel waste, with particular emphasis on how these changes might affect groundwater flow and radionuclide migration; and
3 obtain geotechnical information required to support the engineering design of the disposal system.

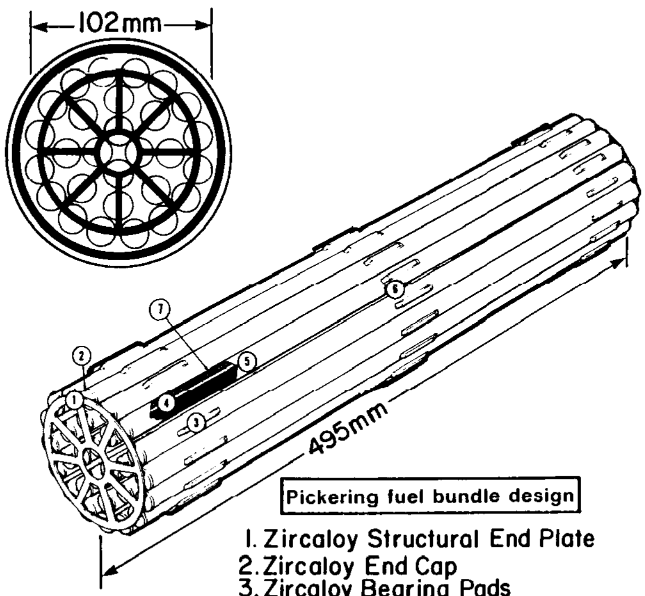

Figure 3 A typical CANDU fuel bundle assembly.

This technology can be generally applied to plutonic rock, whether it is exposed at the surface or lies beneath a layer of sedimentary rock. The major impact of thick overburden or sedimentary cover is additional cost associated with extra hydrogeological testing and monitoring in boreholes drilled and instrumented in the overburden. These are required to relate the groundwater flow system in the sediments to that in the underlying rock mass.

Nature of Nuclear Fuel Waste

A typical CANDU fuel bundle is shown in Figure 3. The uranium dioxide fuel is in the form of ceramic pellets that are sealed inside zirconium alloy tubes, which are assembled into a bundle. When first removed from the reactor, used-fuel bundles are intensely radioactive (1.5 million Ci at discharge). After 1 year of cooling, the intensity of the radiation has decreased by a factor of 100 (15,000 Ci), and the heat generation rate has decreased to 60 W. In 10 years, the radiation intensity has decreased by a factor of 1,000 (1,500 Ci) and the heat generation rate to 4 W.

Table 1 compares the composition of a typical used CANDU fuel bundle, after cooling for one-half year, with that of an unirradiated fuel bundle. The hazard from penetrating gamma radiation is negligible after about 500 years. However, some of the long-lived radionuclides, such as iodine-129 (16 million year half-life), cesium-135 (2.3 million year half-life), technetium-99 (210,000 year half-life) and plutonium-239 (24,500 year half-life) remain toxic for hundreds of

Table 1: CANDU Fuel Bundle Composition (g)

Constituent	*New*	*Used**
Uranium-238	18,865	18,725
Uranium-235	134	44
Other Uranium Isotopes	1	15
Plutonium		71
Other Actinides		1
Iodine		1
Cesium		11
Technetium		4
Other Fission Products		128
	19,000	19,000

*Assuming a burnup of 650 GJ / kg and a cooling time of 0.5 years.

thousands of years, and are the most important radionuclides from a radiological view point. Their potential hazard is similar to that of many non-radioactive toxic wastes. The long-lived radionuclides can do harm only if they are ingested or inhaled.

The plutonium in used fuel is not, strictly speaking, a waste material; it could be recovered by reprocessing and recycled to produce more energy. If the used fuel were reprocessed, the resulting liquid waste would be converted to a highly insoluble glass or glass-ceramic form.

Sodium aluminosilicate glasses have been developed as potential matrices to contain calcined fission product wastes derived from the PUREX process. The resulting waste form has been found to be superior to that based on borosilicate glass and, over a wide range of composition, has a low leach rate in saline groundwaters characteristic of the Canadian Shield [Tait and Mandolesi 1983]. However, aluminosilicate glasses have higher viscosities than borosilicate glasses, which makes their melting and pouring impractical using conventional Joule-heated melters.

Glass-ceramics, based on the natural mineral sphene, have been shown to give further improvements in leach resistance [Hayward 1986]. In this composite material, the sphene is present as a crystalline phase within a continous matrix of durable aluminosilicate glass. The sphene contains a significant fraction of the fission product ions in solid solution, and has been found to be highly resistant to dissolution in many geochemical environments. The composite material can be produced using established glass-making technology: casting from temperatures between 1,250 C and 1,350 C, and controlled recrystallization by reheating to between 900 C and 1,050 C.

Disposal Concept

Either used-fuel bundles or immobilized reprocessing waste would be sealed in corrosion-resistant containers. Figure 4 shows a conceptual design for a thin-walled, particulate-filled container, containing 72 CANDU fuel bundles. Prototype containers of this design, with a 4-mm thick titanium alloy outer shell,

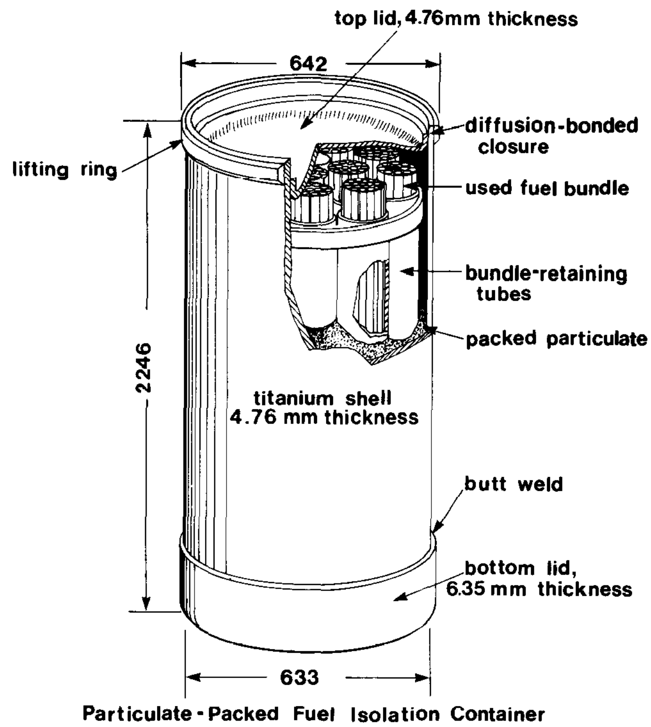

Figure 4 Conceptual design for a thin-walled, particulate-filled container for used CANDU fuel.

have withstood external pressures up to 10 MPa at 150 C, meeting the primary structural requirements for disposal in a vault at a depth of 1,000 m (Teper 1985). Titanium alloys have been found to have sufficient corrosion resistance to provide leak-tightness for at least 500 years, the time during which the hazard is greatest [McKay 1984]. Corrosion experiments indicate that copper would also be an acceptable material for the outer shell.

The disposal vault, shown in Figure 5, would resemble a conventional mine in hard rock, although the quality of the excavation would be superior to that normally required in a conventional mine. A 2-km square network of disposal rooms and access tunnels would be sufficient to dispose of about 190,000 Mg of used CANDU fuel (10 million bundles). It would take about 40 years to fill the vault. Note that the committed 15,500 MW Canadian nuclear-electric generating system, if operated to the year 2,050, would produce about 120,000 Mg of used fuel.

The waste containers would be lowered through a vertical shaft to rooms excavated in the rock mass, 500 m to 1000 m beneath the surface, and placed in holes bored into the floor of the rooms. Prior to receiving the waste containers, the holes would be filled with a mixture of sodium-bentonite clay and sand, mechanically compacted and then rebored to provide a central hole. The clay-sand buffer acts as a diffusion barrier to the movement of groundwater, inhibiting the transport of radionuclides away from the container

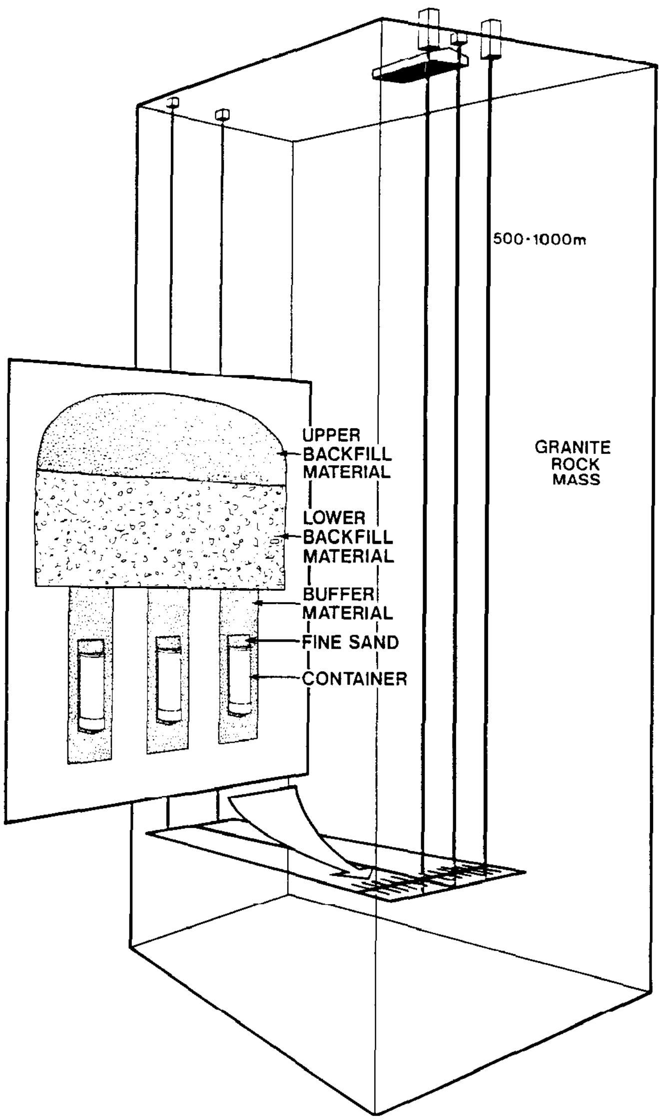

Figure 5 The Canadian concept for a nuclear fuel waste disposal vault.

[Cheung and Chan 1985]. The clearance space between the container and the buffer would be filled with sand.

When filled with waste containers, each room would be backfilled and sealed. The backfilling would be done in 2 stages: first, the lower portion of the room would be filled with a mixture of clay and crushed granite, which would then be mechanically compacted; second, the remaining space would be filled, probably pneumatically, with a mixture of granite aggregate and bentonite-clay. To close the vault, the access tunnels would be backfilled in a manner similar to the disposal rooms, and the access and ventilation shafts would be fitted with a series of bentonite-clay / contrete seals, separated by a backfill mixture of compacted clay and crushed granite.

Post-Closure Behaviour

Vault

After vault closure, as the backfilling materials are saturated with groundwater from the surrounding rock, the bentonite-clay would swell to complete the sealing of containers and disposal rooms. Complete saturation of the buffer and backfill materials is expected to take a few hundred years. Experiments show that the backfilling materials would be as impermeable to groundwater as the surrounding rock.

Heat transferred from the waste containers would gradually raise the temperature of the buffer and backfill materials, and the surrounding rock. Thirty years after a disposal room is closed, the container shell temperature would reach a maximum of about 100 C. About 200 years after closure, the shell temperature would decrease to about 80 C, and then remain at this temperature for another 1,300 years, before decreasing very slowly to the ambient temperature of 15 C. The temperature of the buffer and backfill materials would follow that of the containers, reaching a maximum average temperature of 85 C after about 50 years.

At the depth proposed for a disposal vault, the groundwater is expected to be highly saline, containing high calcium and sodium chloride concentrations [Fritz and Frappe 1982]. The salinity decreases with decreasing depth, and carbonate-rich groundwaters are typically found at shallower depths. Thus, the composition of the groundwater that saturates the vault will depend on its source, and this will in turn depend on the hydraulic conductivity of the rock mass around the vault.

Initially, the groundwater would react with the backfill and buffer materials [Vandergraaf 1987]. The more soluble ions would be leached from the crushed rock, leading to an increase in the pH of the groundwater because of the substitution of alkali metal ions on the surface of the crushed rock by hydrogen ions from the groundwater. The ionic strength of the groundwater may increase slightly. Also, air trapped during backfilling could oxidize ferrous-iron-containing minerals and any organic material present, leading eventually to reducing conditions.

Radiolysis of the groundwater near the waste containers would produce hydroxide and oxide radicals. The oxide radicals would in turn react with ferrous-iron-containing minerals, thus competing with entrapped oxygen, and increasing the time to reach reducing conditions. It should be noted that the chemical reaction rates would be extremely slow and might take thousands of years to reach equilibrium.

After interacting with the groundwater for several hundred years, some container shells would corrode sufficiently to allow the groundwater to come into contact with the used fuel. The rate at which radionuclides could be released is shown in Figure 6

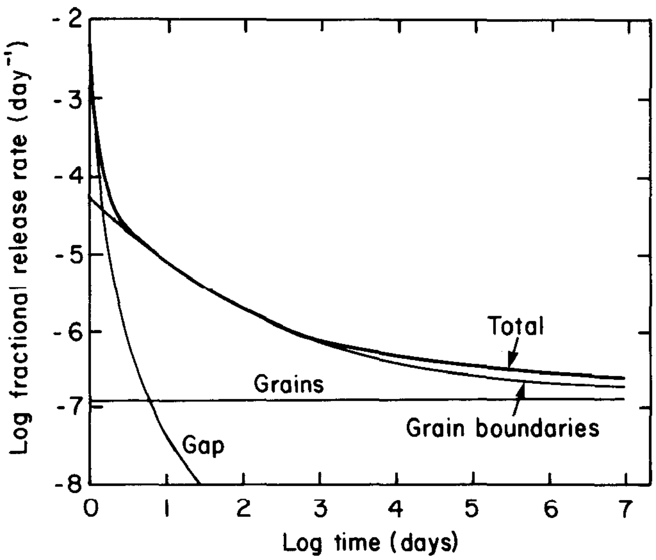

Figure 6 Release of radionuclides from CANDU fuel.

[Garisto *et al.*, to be published]. There are 3 principal release mechanisms:

1 *A rapid release of a fraction (about 2%) of the iodine and cesium when the fuel sheath is breached.* This instant release occurs from spaces between the fuel pellets and sheath, to which volatile fission products migrate during irradiation.
2 *Slow release of the remaining inventory of iodine and cesium by preferential dissolution at the grain boundaries.* The rate of release depends on the irradiation history, which affects the fuel microstructure. In fuels that have been irradiated at high power, the porosity at the grain boundaries is interconnected, allowing water to percolate through the fuel and contained fission productions to escape. In fuel irradiated at low power, there are few interconnected pores, and the release of fission gases is then mainly controlled by dissolution of the uranium dioxide grains and grain boundaries.
3 *Extremely slow release of the remaining fission products and actinides trapped within the uranium dioxide grains by congruent dissolution.* The rate of dissolution is determined by the groundwater redox conditions, lower releases occurring under reducing conditions.

The behaviour of the radionuclides in the vault would depend strongly on the groundwater composition, the temperature, and the minerology in the vault. Cesium and iodine are highly soluble. However, cesium sorbs strongly onto clay materials and phyllosilicates by an ion exchange mechanism, if the ionic strength of the groundwater is low. Iodine does not sorb on natural minerals. Technetium, which is multivalent, has a complex behaviour: under oxidizing conditions it forms poorly sorbing anionic species; however, under reducing conditions it is only slightly soluble and will be present in groundwater only at very low concentrations. The actinides also have multivalent oxidation states. In their reduced state, they also tend to be only slightly soluble; in their higher oxidation states they are more soluble, and tend to form complexes with anionic species such as chloride and carbonate. Thus, a certain fraction of the released radionuclides would be precipitated or sorbed on mineral surfaces, depending on the radionuclide and on the composition of the groundwater. The fraction that remained in solution might diffuse into the connected pore space in the rock matrix, or might be transported by groundwater through any fracture networks.

Rock Mass

Groundwater generally moves in a rock mass because of a three-dimensional potential field that provides the driving force. The configuration of the potential field depends on the particular forces (gravity or temperature) within the region containing the rock mass, the geometry of the region and the flow conditions at its boundaries, and the nature and variation of properties that control flow within the region. Our field research, described in more detail later, indicates that the plutonic intrusives of interest can be conceptualized as relatively large rock volumes with low permeability, separated by relatively thin planar fracture zones. The fracture zones are much more conductive than the background rock, and control the groundwater flow. The flow is primarily driven by topographic gradients, which in the Canadian Shield are small on a regional scale.

The rate of movement of dissolved and suspended radionuclides would be affected by sorption and mechanical dispersion, which would tend to reduce the velocity of the radionuclides relative to that of the groundwater. The surfaces of fractures are coated with alteration minerals. Radionuclide ions in solution, such as cesium, plutonium, and technetium, can participate in exchange reactions with these alteration minerals, resulting in a reduction of the radionuclide concentrations in solution. Also, the heat generated by the waste will set up a temperature gradient, and thermal cycling of groundwater may occur. Minerals that go into solution in the vault, which is higher in temperature than the surrounding rock, may precipitate when the groundwater is cooled by the rock mass. The precipitation of alteration minerals will tend to decrease the fracture aperture, and some fractures may seal.

Mechanical dispersion is a mixing phenomenon. It causes a convective front of radionuclides moving through the rock matrix to spread laterally and longitudinally, and thus to dilute. Diffusion, mass flow caused by a concentration gradient, is a secondary component of the dispersion mechanism that also contributes to dilution. It is significant only when convective transport is very slow. Nonsorbing radio-

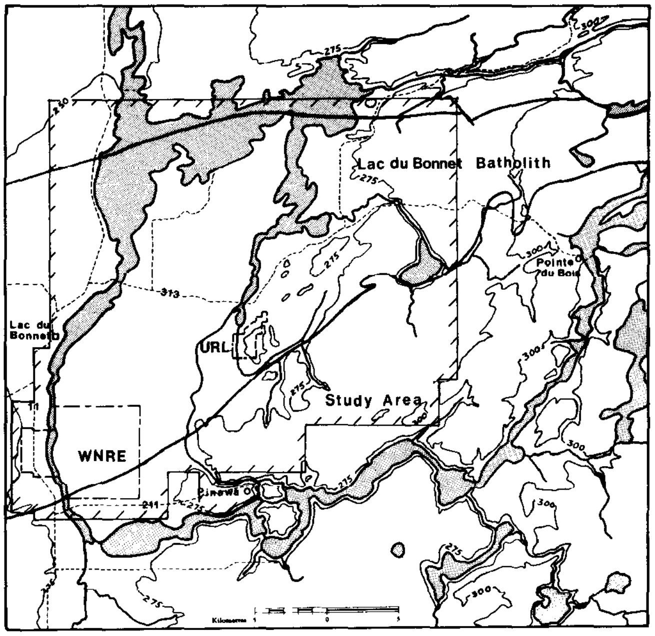

Figure 7 Location of the Whiteshell Research Area

nuclides, such as iodine, diffuse readily through the connected pore space of the rock matrix. Also, if sorption is depressed, by an increase in the ionic strength of the groundwater, diffusion of even trace concentrations of cesium has been shown to take place over distances of 100 mm in periods as short as 6 months.

Field Research Areas

Field research areas have been established at 3 locations in the Precambrian Canadian Sheild: in the Atikokan and East Bull Lake regions of northern Ontario, and in the Whiteshell region of southeastern Manitoba. Since 1978, these research areas have been extensively characterized from a geotechnical perspective and monitoring of the groundwater flow system in each area is continuing via instrumented networks of boreholes. Field work on a smaller scale is also continuing at AECL's Chalk River site.

The Whiteshell research area (see Figure 7) is now the main focus of our field studies. This region contains the Whiteshell Nuclear Research Establishment and AECL's Underground Research Laboratory (URL), and provides a unique opportunity to validate site characterization methodologies at the scale now thought necessary to characterize a candidate disposal site. The region is situated on the Lac du Bonnet Batholith, a large granite pluton similar to many found in the Canadian Shield. There is a moderate topographic slope across the region of about 50 m from the southeast to the northwest. The Winnipeg River provides stable hydrological boundaries: along the east side of the region the river is controlled at about

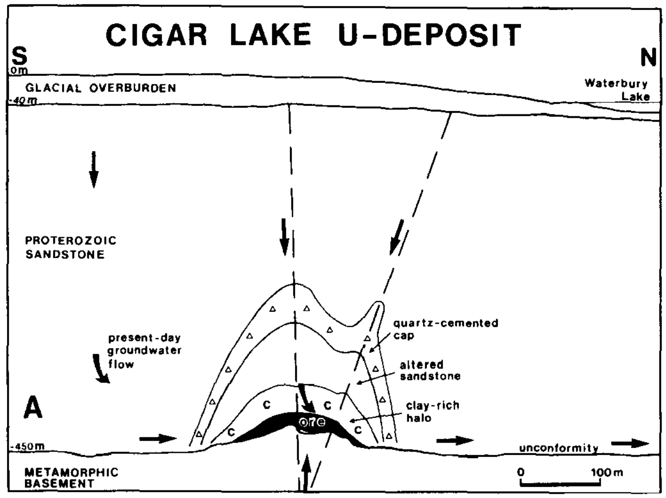

Figure 8 Cigar Lake Uranium Deposit: a natural analogue for some aspects of disposal vault geochemistry.

273 m, along the south at about 273 m, and along the west at about 254 m.

Cigar Lake

The Cigar Lake uranium deposit is located in northern Saskatchewan and is the focus of a study aimed at gaining insight into long-term geochemical processes [Cramer 1986]. The ore body has survived for 1.3 billion years in a relatively open groundwater system and has no direct chemical or physical signature at the surface.

The deposit is situated at a depth of 430 m, at the interface between the host sandstone formation and the underlying basement rock of the Archean Shield. The ore body is lens-shaped (2,000 m long, 100 m across, and 20 m thick at mid-length), and is capped by a 5-m- to 30-m-thick clay-rich halo. An iron oxide / hydroxide-rich zone forms the contact between the high-grade ore and the clay-rich halo. The average ore-grade is 14% U_3O_8, with local concentrations as high as 60%.

Figure 8 shows a cross section of the deposit in the north-south direction, which coincides with the direction of groundwater flow now. Near the ore body, groundwater flows along a zone of relatively high hydraulic conductivity between the sandstone and the basement rock. The ore body is situated at the intersection of the interface with a number of near-vertical fractures. The local alteration of the sandstone and the uranium mineralization is attributed to hot, reducing water discharged from the basement rock into the sandstone through these fracture conduits. The most plausible mechanism for the formation of the deposit is precipitation of dissolved uranium from local groundwaters, caused by interaction with the hot, reducing water discharged from the basement rock. Alteration of the sandstone is characterized by changes in its

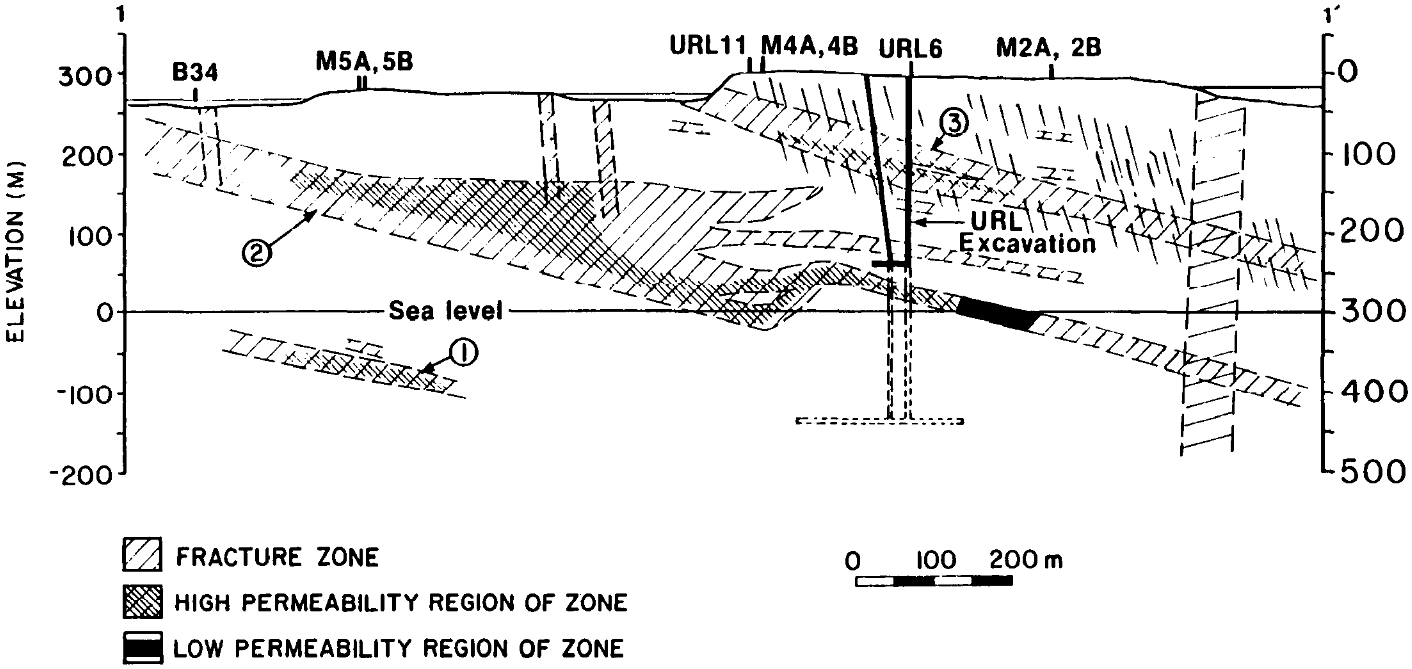

Figure 9 Cross section showing fracture zones in the rock mass containing the URL.

colour and by the clay content. Quartz, in solution, migrated down the thermal gradient and precipitated in the cooler, less altered sandstone to form the quartz outer layer of the cap.

The composition of the ore body is relatively simple: a high concentration of uranium, very small concentrations of other actinides and lanthanides, and extremely small concentrations of radionuclides formed by uranium decay and by natural fission of uranium. The higher uranium concentrations within the quartz cap are consistent with the hydrothermal process that resulted in the formation of the cap and the ore body. There has been no enrichment of uranium on secondary minerals found on open surfaces of fractures in the sandstone further away from the quartz-cap.

The geochemical questions of particular interest are: How did the ore body survive for so long in such an open system saturated with groundwater? What transport and fixation mechanisms influenced the migration of radionuclides in the host rock? Answers to these questions are the focus of our ongoing investigation at Cigar Lake, and will provide insight into the processes expected to control radionuclide movement in a disposal vault.

Hydrogeology

A detailed understanding of the hydrogeology of a candidate rock mass is essential to assess its acceptability. Our methodology for gaining this understanding is derived from a structured process which integrates the various geoscience disciplines. First, the geological features of the rock mass that control the groundwater flow, and the associated physical, chemical, and hydrological characteristics, are determined from field investigations. Then, these geological features and their characteristics are interpreted to establish a conceptual model of the groundwater flow system. Next, based on the conceptual model, a detailed 3-dimensional mathematical model of the flow system is used to predict changes caused by natural and artificial perturbations of the rock mass and flow system. Finally, comparisons are made between predicted and measured responses, to test the conceptual and mathematical models, and to refine them so that, together, they provide a realistic representation of the actual groundwater flow system. As an illustration, a description follows of the methodology as it was applied to the characterization of the site for the URL [Davison 1985].

Over 100 boreholes were drilled into the shallow overburden deposits and into the underlying granite to depths up to 1,100 m. Fractures were characterized in the boreholes, using a number of techniques: by detailed core-logging methods, by in-hole television camera equipment, and by a variety of standard and innovative borehole geophysical logging techniques. Hydraulic conductivity measurements were made at selected intervals in individual boreholes. In addition, interference tests were done, in which water was either injected or withdrawn from one borehole, while groundwater pressures were measured in isolated intervals in neighboring boreholes. These tests provided an understanding of the hydraulic conductivity of the portion of the rock mass between the boreholes.

Analysis of the information obtained from the field investigation identified 3 major fracture zones, shown in Figure 9, dipping at about 20 degrees to the horizontal. The upper and lower zones are relatively uniform and have thicknesses of a few metres. In contrast, the middle fracture zone has a complex geometry, with a number of off-branching limbs. At the surface of the batholith, the fracture zones coincide with major discontinuities identified during geological mapping.

The fracture zones control the movement of groundwater and, within the zones, there is a wide variation in hydraulic conductivity. Regions of high and low conductivity were determined by continuous monitoring of the hydraulic pressure in isolated intervals in the network of boreholes during interference tests. Outside the fracture zones, the rock is relatively unfractured, except for sets of near-vertical fractures that extend from the surface to depths from 100 m to 300 m. These vertical fractures are oriented roughly parallel to the direction of the maximum principal stress.

To describe this conceptual model mathematically, a finite-element computer model, called MOTIF, has been developed [Guvanasen 1985]. It represents the relatively unfractured background rock by an equivalent porous medium, composed of 3-dimensional continuum elements. The high-conductivity zones are represented by special planar elements, which are embedded in the background porous medium. The flow within these planes is dominant along their axes. The 3-dimensional flow field within this assembly of blocks and planar elements is described by porous medium flow equations.

To test these models, the response of the groundwater flow system to the excavation of the URL shaft was predicted at 171 isolated intervals in the network of boreholes used to characterize the rock mass [Guvanasen *et al.* 1985]. These predictions were then compared to the measured responses as the excavation proceeded [Davison 1986].

Figure 10 shows the measured and predicted rate of groundwater flow into the shaft during excavation. The first inflow occurred when several water-bearing near-vertical fractures intersected the shaft walls. The rate of inflow increased as the excavation passed through the upper fracture zone. Notice that the inflows predicted by the MOTIF computer model are generally greater by a factor of three. The predicted maximum inflow occurred as the upper fracture zone was penetrated. At the time the prediction was made, the presence of the vertical fractures was unknown. Subsequently, the predicted rate of inflow gradually declined to a constant value, consistent with the measured inflow.

Figure 11 shows a comparison between measured and predicted histories of hydraulic head at one of the monitoring locations in the upper fracture zone. The onset of the sharp drop in hydraulic head corresponds to the onset of inflow to the shaft. The agreement between prediction and experiment is generally good. The deviations during the period March 1985 to April 1986 are attributed to seasonal variations in recharge, which were not included in the mathematical model. This agreement is typical of that attained at all monitoring locations used in the comparisons, and gives us confidence that the methodology is sound.

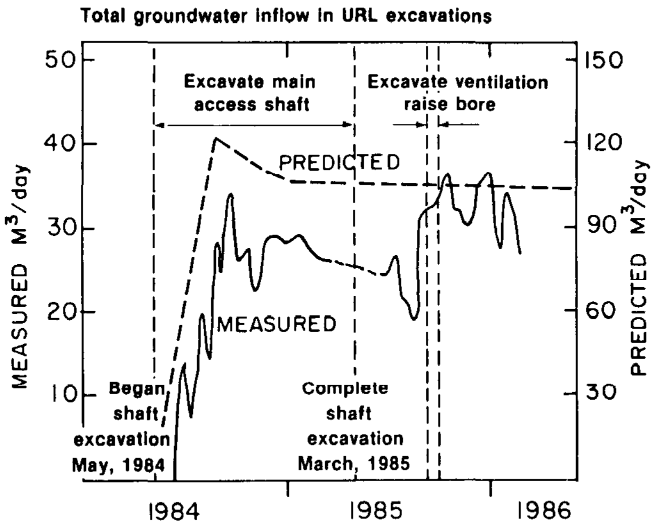

Figure 10 Comparison of predicted and measured groundwater inflow into the URL shaft.

The area involved in the investigation described above is much smaller than would be required to characterize a candidate disposal site. So we ask: Can the methodology be transferred to the regional scale, where distances between recharge and discharge can be as much as 10 km to 20 km?

To answer this question we have begun an investigation of the entire Whiteshell research area to a depth of at least 1,000 m. The scope of the field investigations includes: conducting additional detailed geological

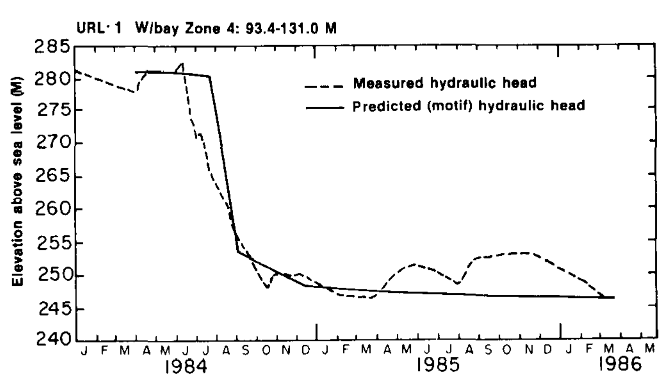

Figure 11 Comparison of predicted and measured hydraulic head of borehole URL-1 in the upper fracture zone.

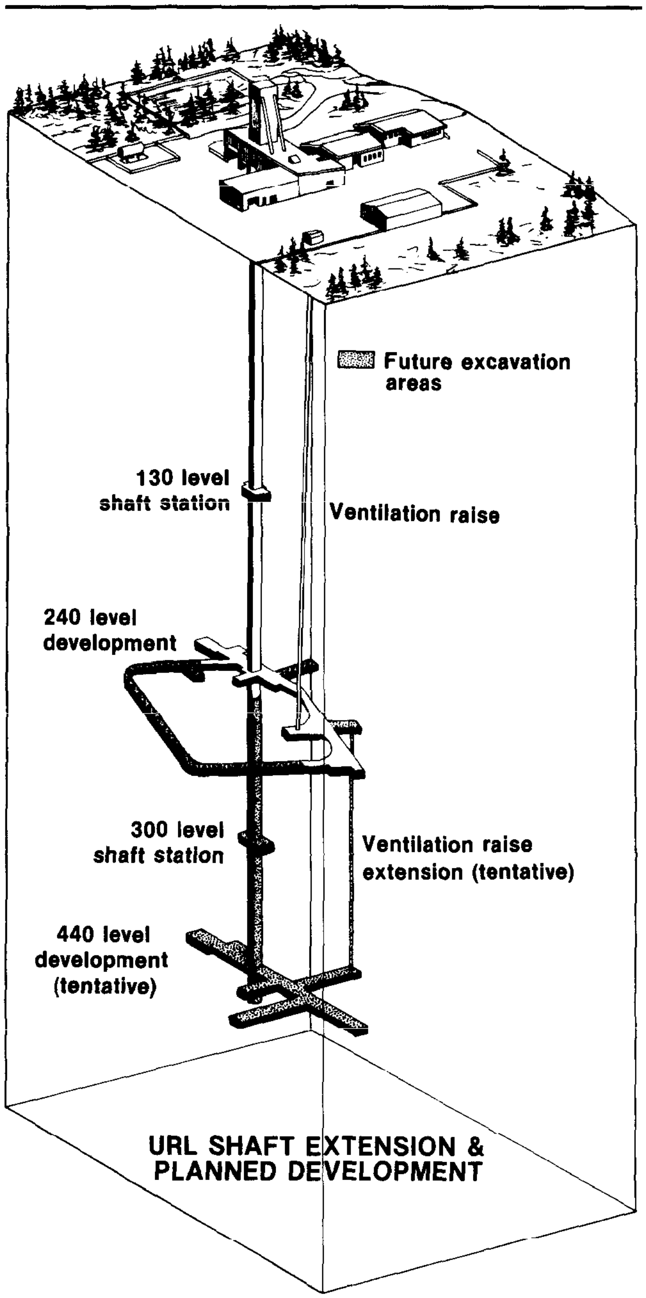

Figure 12 Schematic of the Underground Research Laboratory.

and geophysical surveys in the region; drilling, logging, and instrumenting a network of deep boreholes; and monitoring the groundwater chemistry and hydraulic head fluctuations in the network of boreholes. The areas of particular interest are: the boundary of the batholith; major surface features that are possibly structural discontinuities, such as faults or fracture zones; and the subsurface geological structure and groundwater head distribution.

Underground Research Laboratory

Construction of the URL is now at an advanced stage. It is being constructed in a part of the Whiteshell research area which had not been previously disturbed. The excellent outcrop in the area facilitated the geological characterization of the site. The location of the access shaft and underground laboratory rooms was based on knowledge of the underlying geological structure and groundwater flow system derived from extensive geological and hydrogeological characterization, beginning in 1979. The characterization of the granite rock mass and the excavation of the shafts and rooms contributed directly to the development of a comprehensive methodology to characterize disposal sites and to evaluate their isolation potential. To date, work at the URL has provided unique information on the response of the rock mass and its groundwater flow system. Construction of the URL has also allowed us to test excavation techniques that could be used to construct a disposal vault, particularly drilling and blasting procedures that minimize damage to the rock near excavation surfaces.

The present state of underground development at the URL is shown in Figure 12. The excavations include a 3 m by 4 m rectangular access shaft and a 2-m-diameter ventilation shaft, both 250 m deep, and laboratory rooms excavated at a depth of 240 m. Preparations are underway to extend the access shaft to a depth of 455 m as part of an agreement with the U.S. Department of Energy. The shaft extension will pass through a highly permeable fracture zone just below the 255-depth, and work is underway to characterize and grout this zone prior to beginning the excavation. Excavation of the shaft extension will take place in the period June 1987 to September 1988, and its geotechnical characterization is expected to be completed by September 1989. The rock mass around the shaft at the 455-m level will also be characterized to select sites for experiments. Included will be experiments to study how the rock mass responds to heating, how contaminants and groundwater move through the rock mass, and how various sealing methods perform.

Conclusion

The understanding of basic physical and chemical processes derived from the laboratory and field investigations highlighted above has been incorporated into a mathematical model that describes the complete disposal system for assessments of long-term safety. This model of the disposal system links individual mathematical models for the vault, rock mass, and surface environment to provide an estimate of the range of possible effects to individuals at some future time from an implementation of the disposal technology. This methodology has been developed to conform with the basic safety criteria, and we are confident that it will provide an accurate assessment of the disposal concept's safety.

An innovative methodology for characterizing the hydrogeology of a plutonic rock mass has been successfully applied and validated in the field to a depth of 400 m. This methodology is now being applied at a regional scale comparable to that required to characterize a candidate disposal site. Based on our experience to date, we are confident that the process by which detailed *in situ* measurements are used (to develop a conceptual model of the hydrogeology of a site which is then idealized into a three-dimensional description) is generally valid.

Our field investigations in the Canadian Shield, supported by assessments of conceptual disposal vault designs, give us confidence that there are a large number of locations which, after detailed examination, will provide disposal sites that meet the basic safety criteria.

Acknowledgements

This paper was originally presented at the Canadian Engineering Centennial Conference, Montreal, 18–22 May 1987.

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