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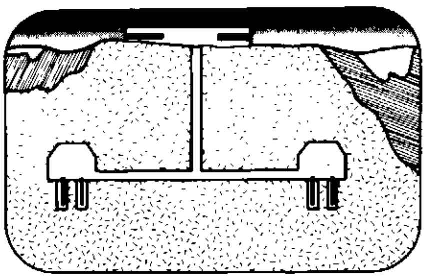

Underground Disposal of Canada's Nuclear Waste

H. Y. Tammemagi
Atomic Energy of Canada Limited
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba R0E 1L0

J. F. Gale
Terrain Sciences Division
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

B. V. Sanford
Regional and Economic Geology Division
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

Introduction

The nuclear industry, in common with other industrial activities, produces both benefits and certain undesirable by-products. The benefit is electrical power, which forms the foundation for our modern-day way of life. The undesirable by-products are the wastes generated during the fission of uranium. These are radioactive and toxic, and must be shielded, contained and cooled until they no longer pose a threat to the health and environment of mankind. Two kinds of radioactive elements are involved. Fission products, which emit penetrating radiation (beta and gamma rays), have relatively short half-lives and thus cooling and shielding are only necessary for approximately 300 years. Actinides, which emit relatively unpenetrative alpha particles, have long half-lives so that containment will be necessary for hundreds of thousands of years. Hence, it will be necessary to construct a facility which must provide shielding and heat dissipation for the short term, and containment for the long term. It must remain intact for much longer periods of time than any other man made structure.

A natural solution is to place the wastes deep into subsurface formations which are known to have been stable for many millions of years and which will undoubtedly remain so for a considerable period. It is appropriate that the nuclear cycle should end where it began, with the radioactive elements emplaced in the protective custody of the earth's crust.

The purpose of this paper is to describe radioactive wastes and the scientific programs which are in progress and planned to ensure their long-term subsurface isolation. A program to determine the feasibility and safety of geological disposal of nuclear wastes by developing and constructing a test repository in a suitable rock formation was initiated in 1975. The project is under the direction of Atomic Energy of Canada Limited (AECL) in collaboration with the Geological Survey of Canada (GSC), the Canada Center for Mining and Energy Technology (CANMET) and Earth Physics Branch (EPB), all of the Department of Energy, Mines and Resources. In addition, industry and universities are contributing to the program.

A broad spectrum of geoscientific involvement is necessary to bring the program to a successful conclusion. Expertise is required in disciplines as diverse as stratigraphy, sedimentology, petrophysics, petrology, hydrology and theoretical rock mechanics, to name only a few. Although the project is essentially an exercise in engineering, there will be a considerable requirement for pure and applied science. Furthermore, much of the acquired basic data will be applicable to fundamental problems.

Many radioactive waste disposal concepts have been proposed. However, a fundamental guideline which has been adopted for the Canadian program is that concepts which rely on future development of new technology shall not be considered at this time. Thus, polar ice sheet disposal, deep space ejection, sea floor disposal, extremely deep borehole emplacements and similar concepts have been excluded. An additional constraint is that the wastes shall remain accessible for some period after their emplacement (probably several decades) in order to permit surveillance and to allow for the possibility of retrieval.

These constraints are satisfied by an excavated facility consisting of a grid of tunnels on one or more levels, at some considerable depth (300 to 2000 m) within a carefully selected geological formation. Surface facilities will receive the radioactive wastes and lower them through a shaft to the repository where they will be transported to appropriate locations and emplaced below the tunnel floors. Before they are brought to the facility, the wastes will have been solidified into a leach-resistant form, such as glass, and then encapsulated in cylinders. The conept is illustrated in Figure 1.

The anticipated volumes of nuclear wastes are not large. The heat generated by the radioactive decay of the wastes, rather than their volume, will determine the size of the disposal facility. Preliminary estimates based on projections of nuclear energy demand and on "acceptable" temperature levels indicate that the subsurface area required for a one-level repository will be about one km^2 by the year 2000 and about eight km^2 by 2050.

The repository is scheduled to be ready to receive nuclear wastes on a full time basis by the year 2000. To achieve this deadline, a site will have to be selected by about 1981 with the construction of a demonstration facility complete by about 1986. Careful monitoring and surveillance will follow for the ensuing 10 to 15 years as electric heaters and nuclear wastes are emplaced on a trial basis.

The Geological Medium

The main objective during the next few years will be to determine the most suitable type of host rock for the disposal of radioactive wastes. Specific sites will then be selected and investigated ultimately yielding one site which will be developed into a demonstration facility.

A review of rock types and their characteristics, as related to the requirements of the repository, has indicated that two, in particular, merit detailed investigation – plutonic crystalline rocks, and salt deposits. In addition, serpentinized ultra-mafic rock is being considered.

Plutonic crystalline rock has a number of characteristics that suggest it will be an acceptable host. Plutons with dimensions suitable for a repository are abundant in the Canadian Shield. Most are relatively homogeneous in composition and structurally competent so that it would be possible to design and construct a repository which will remain mechanically stable and therefore accessible for a considerable time. The central regions of plutons are seldom associated with mineralization and thus form unattractive drilling targets for future generations. The stability, low seismicity and low geothermal gradient of the Canadian Shield, as well as its central location in Canada relative to present and planned nulcear reactors, are advantageous for the siting of a repository.

However, the utilization of plutonic rock is not without potential disadvantages. Since discontinuities such as joints and fractures will always be present to some degree in an igneous rock mass, a possible way by which the radionuclides can return to the biosphere is by the leaching of the solidified wastes and their subsequent transport by ground water. Therefore the assessment of fracture permeability and ground water flow, especially over long periods of time, will be of fundamental importance.

Salt (halite) formations have a number of physical attributes that may make them suitable for disposal of nuclear wastes. They are good conductors of heat, and are thus capable of dissipating the heat generated by the spent fuel wastes, they have self-sealing characteristics which may be beneficial in the event of minor fracturing or exposure to excessive heat, and they are geologically stable over vast areas of Canada. The fact that present-day halite deposits have avoided removal by solution for several hundred million years demonstrates that certain of these deposits lie within closed systems that have been long remote from the biosphere.

Halite deposits are present in the subsurface of every Province and Territory of Canada. Thus, if salt is selected as the host rock, the extensive geological research and development required to establish the first facility could be applied in large part to similar geological terrains in other parts of the country if the requirements for disposal capacity increase in the years to come.

The utilization of salt deposits for radioactive waste disposal is also not without certain potential hazards. Sedimentary basins often contain prolific aquifers above and below the salt zones and it is vital that the repository

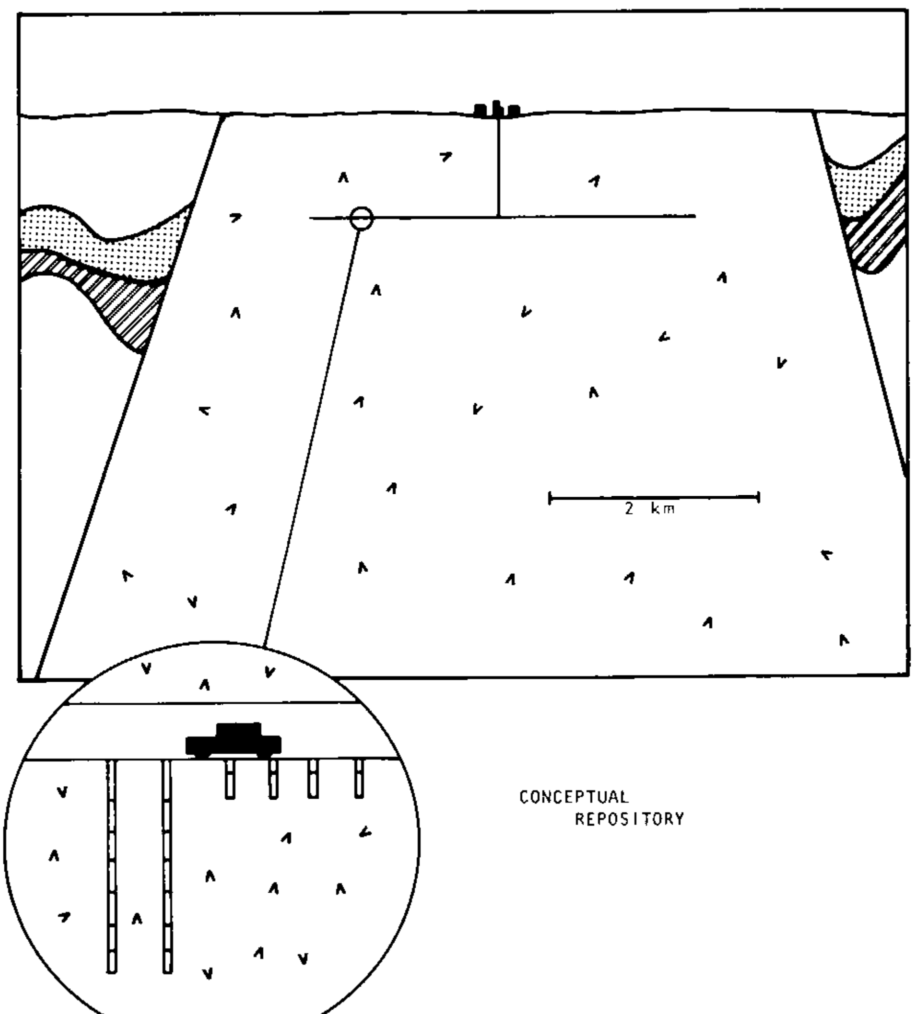

Figure 1
Schematic cross-section of a conceptual repository for nuclear waste disposal

remain isolated from them. Salt deposits are often associated with oil, gas and potash, and it must be ensured that future generations in the quest for mineral resources do not unsuspectingly drill into or encroach upon the repository. In addition, the plasticity of salt may limit the length of time for which the wastes are retrievable.

The main emphasis of the Canadian program is on the preceding two rock types. However, serpentinite (here denoting ultra-mafic rock with *any* degree of serpentinization) is also being investigated. Due to its hydration it behaves plastically at depth and elevated temperature, yet is structurally competent near the surface. Serpentinite thus has some of the properties of salt and it is, of course, insoluble. However, in Canada there may be difficulty in finding bodies of appropriate dimensions which are not associated with economic mineralization or seismic zones.

Plutonic Rock

Igneous intrusive rocks (plutons) constitute a major fraction of the exposed bedrock in the Canadian Shield of central Canada (Fig. 2). Unlike salt desposits, which have been studied quite intensively in the United States and the Federal Republic of Germany, little information is available concerning waste emplacement into igneous rocks. As a result, the program described in this section has had to begin at a fundamental level and encompass a broad range of research.

Assessment of igneous rocks as potential host rocks for a nuclear repository was initiated by compiling a list of factors that were considered to be important in the selection of the type of rock and the location for the repository. These factors fall into three principal categories: 1) geological and geotechnical, 2) site and environmental, and 3) legal and political (Table I). Ongoing efforts are being directed

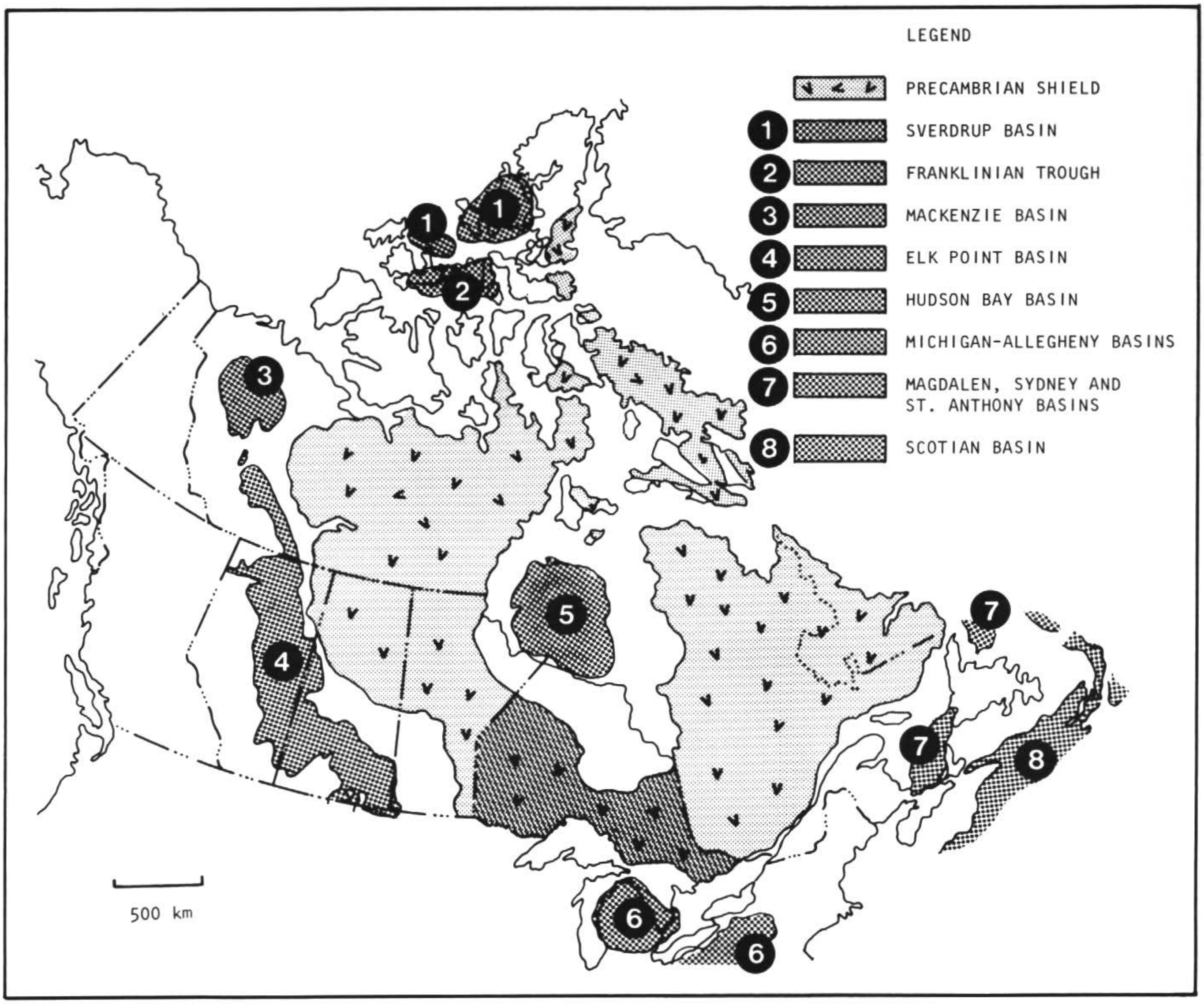

Figure 2
The Canadian Shield (showing area of immediate interest for radioactive waste disposal by oblique hatching) and salt basins of Canada.

Table I *Factors for Cosideration*

A. Geological and Geotechnical

1 Economic value
2 Structural Geology
—tectonic framework
—dip and nature of rock mass
—major lineaments - frequency,
—orientation and charcter
—fracture frequency and orientation rock fabric
3 Short and long term stability of underground openings
structural integrity of rock mass
—depth, thickness, and extent of both host rock and adjacent rocks
—mineable depths
existing stress field
—rock strength properties as a function of time and temperature
4 Rock characteristics
—petrology and mineralogy
—rock homogeneity or purity
- ion exchange properties
—content of gases and liquids and temperature stability field
—permeability and porosity of both fractures and rock blocks
5 Erosional stability over geological time
6 Thermal properties of rock over specified temperature ranges expansion, conductivity, fracture potential, etc
7 Effect of thermal stress gradients on fractures and rock properties
8 Effect of fracutres on the heat transfer properties of the rock mass
9 Groundwater flow in the vicinity of high thermal gradients
10 Effect of hydration and dehydration
11 Effect of radiation on structural properites

B. Site and Environmental

1 Accessibility rail or road
2 Distance from major population centres and waste load centres
3 Distance from areas of restricted land use
4 Availabilty of buffer zone
5 Topography
6 Hydrology and hydrogeology
7 Overburden characteristics
8 Association with known mineral
9 Mining and drilling activity
10 Mine waste disposal
11 Seismicity - natural and induced
12 Geothermal environment
13 Future geological events, i.e. glaciation
14 Possibility of site operation being affected by other, nonwaste related, industrial accidents

C. Legal and Political

1 Existing land use rights
2 Alternate use conflicts
3 Population density
4 Safe security
5 Public acceptance

towards ranking and quantifying the various factors in each category

Since the Shield is so immense that some delimitation is necessary, and since most of the nuclear power generated in Canada until the year 2000 will be in the Province of Ontario, the plutonic rock program has been focused on the Precambrian terrain of that province. Many plutons, encompassing a variety of rock types (mafic to felsic), tectonic settings and geographic locations have been reviewed using available literature, geological maps and aerial photos. About a dozen sites were chosen for reconnaissance mapping during the summer of 1976 by comparing such factors as amount of outcrop, number and size of structural lineaments, accessibility and economic potential. Particular attention was paid to mapping the fracture systems at each site. Further review of potential sites and field mapping is planned.

A number of other studies are currently under way or planned to obtain the data required to demonstrate the feasibility of the concept as well as to develop the criteria necessary for selecting a suitable site. Case histories of underground hydro-electric excavations and operating mines are being reviewed to study ground water conditions in three-dimensions and to correlate surface and subsurface features.

A major geotechnical program is being developed for evaluating potential sites. Data on subsurface conditions will be obtained directly from exploratory boreholes as well as from indirect techniques including airborne, surface and borehole geophysics. A fundamental objective will be the delineation of ground water flow in igneous terrain, particularly at greater depth, since virtually no information on this topic is currently available. Hydrological data for fracture permeabilities and porosities will be obtained using boreholes cameras, injection and pumping tests. Ultimately, any promising site will require further detailed investigation including seismicity monitoring and delineation of the hydrological system on a regional scale. To test equipment and train personnel for these programs, a test site has been established in a granitic body near Ottawa.

Parallel to the evaluation of particular plutons, laboratory investigations of mechanical, thermal and hydraulic properties of various igneous rock types will be undertaken. The effects of radiation and elevated temperatures on these properties will also be determined.

The development of techniques for safety and environmental analyses is an integral part of the program. The analyses will receive input data from laboratory and field experiments and in addition to quantifying the safety of the disposal concept, will specify criteria for selecting suitable sites.

As currently scheduled, drilling on plutonic rock will commence in the summer of 1977 and potential site selection, general field evaluation and laboratory investigations will continue until some time in the period 1980 to 1982, when enough evidence will have been accumulated to choose a specific site.

Salt

The evaluation of salt deposits in Canada as possible host rocks for radioactive waste disposal is being performed in three principal phases. Phase I is an overview (geological reconnaissance) of all of the salt deposits of Canada. Phase II will comprise a further, more comprehensive surface and subsurface synthesis of the favourable areas selected in the Phase I study. This program could lead to the indentification of potential mine-site localities. Phase III will be a drilling program to define the limits of a specific site preparatory to the construction of an underground repository.

The Phase I study, which involved the compilation of data on all the salt basins of Canada (see Fig. 2), was completed in March 1976. This preliminary investigation provided information about the distribution, thickness, depth, structure, of each of the salt units and, where information was available, to the reconstruction of paleography, depositional environments, facies, history and extent of salt leaching, diapirism.

On the basis of Phase I studies, many areas were rejected as potential sites for one or more of the following reasons: excessive depth; inaccessibility beneath ocean basins and far northern terrains; evidence that widespread removal of halite by leaching is still in progress, and the presence of economic or potentially economic deposits such as oil, gas, tar sands, potash.

Three areas have been selected for more detailed (Phase II) studies:
1) Southern part of western Canada Mainland (northeast margin of Elk Point Basin in Saskatchewan and Manitoba),
2) Southwestern Ontario (east shore of Lake Huron bordering Michigan Basin),
3) Various onshore portions of Magdalen Basin in Nova Scotia and New Brunswick.

During Phase II, which is scheduled for completion by the Spring of 1979, surface and subsurface investigations of a multidisciplinary nature will be undertaken. Surface investigations include terrain inventory studies to determine the potential effects of seasonal and long term fluctuations of surface waters, future recurrence of glaciation, land slides, as well as an appraisal of the suitability of the terrain for agricultural, industrial or urban development. The rock units which overlie the salts, where exposed to the surface, will be sampled and tested to determine their water bearing characteristics (porosity, permeability and fracture systems), and lithological competence.

In the subsurface, the lithological charcter of the salt beds and overlying strata will be determined by studying sample cuttings and cores from wells drilled for oil and gas, mechanical well logs and data from mineral exploration, etc. Geophysical (gravity and seismic information will be acquired and integrated with the drill hole data to extrapolate stratigraphic information from one drill to another and to map potential oil and gas-bearing structures.

The effects of groundwater and formation fluids must be carefully assessed to ensure that these will not be a concern during repository operation or in the long term. Hopefully areas will be found where groundwater flows are negligible. Removal of salt due to processes of leaching by groundwater and formation fluids is also a natural hazard, particularly along the margins of most salt basins. Studies are presently being conducted to reconstruct the original depositional edges of salt units, and to establish the progressive migration history of the solution edge. Considerable success has already been achieved in this regard in southwestern Ontario. Studies there indicate that salt leaching was for the most part an ancient phenomenon and is not likely to be a major concern in future.

The culmination of geological exploration in the salt program is Phase III which will involve test drilling of sites selected in the Phase II study. When this stage is reached, all of the available geoscientific data will have been compiled and analyzed, and the drilling will serve to outline the limits of the repository and to confirm whether or not the previously established requirements have been sufficiently met to warrant proceeding with a mine facility.

Serpentinite

A small program to investigate serpentinite in Eastern Canada has been initiated at the University of Quebec at Montreal. Field work in the Abitibi belt and in the Appalachian region was performed in 1975, and currently, laboratory studies are investigating the stability of the serpentinite minerals at elevated temperatures and under irradiation. Further research is planned to study one site in detail with laboratory emphasis on thermal and mechanical properties. The objective is to establish how these properties vary with degree of serpentinization, and hence, in the rock mass.

Repository Development

The ultimate objective of all facets of the program is the design and construction of a test repository which will safely contain nuclear wastes. Considerable design and supporting research is necessary to develop a feasible waste emplacement configuration, repository layout and support facilities. Due to the radioactivity of the materials which are involved, the repository will be more complex than a conventional mine and more stringent standards of safety will be necessary. The heat produced by the wastes poses a particular problem and rock mechanics calculations will be necessary to search for an optimum waste emplacement density while ensuring the stability of the excavated chambers.

A preliminary conceptual design for a repository which could contain all the radioactive waste produced in Canada until 2050 has been completed by Acres Consulting Services Ltd. A reference design was outlined and a number of alternative concepts were described in a general way. Cost estimates indicated that repository construction and operation would have a very small effect on the price of electricity. Analyses to determine temperature distributions associated with various repository models in granitic igneous rock were also performed. The results indicated that it should be possible to keep maximum temperture increases to acceptable limits while maintaining a reasonably sized repository. The stresses created by excavating the repository openings and by the temperature increases were determined and indicated that no insurmountable stability problems should be encountered. It must be noted that these were preliminary studies and incorporated many simplifying assumptions. The next phase of the study will include detailed analyses of the thermal/stress regimes for the reference design and will continue the evaluation of alternative concepts. The objective is to choose a concept and demonstrate its feasibility so that detailed design can commence once a specific site is selected.

Prior to actually sinking a shaft at a chosen site, it will be necessary to verify analytical predictive capabilities as well as to compare *in situ* rock properties and behaviour with those observed in the laboratory. For this purpose a relatively large scale experiment is planned involving electric heaters placed in an operating mine.

The test repository is expected to be completed by about 1986, after which the facility will be tested for a considerable period under rigorous surveillance and monitoring. If the repository satisfies the scrutiny of the trial period and the requirements of the licensing agencies, it could be expanded and converted to an operational repository for Canada's nuclear wastes.

Conclusion

This paper has described a program for the disposal of Canada's nuclear waste deep into the formations of the earth's crust. To achieve the objective of safely isolating the wastes from the biosphere, a broad range of earth science disciplines are required. The intertwining of these disciplines should yield not only a successful outcome to the geological disposal but also provide basic knowledge to fuel fundamental research in Canadian geoscience.

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