THE CANADIAN WASTE MANAGEMENT RESEARCH PROGRAM

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ABSTRACT

AECL is developing a comprehensive understanding of the chemical and physical processes that affect the safety of a waste vault for the permanent disposal of high-level waste. The Canadian waste disposal concept involves the construction of a waste vault 500 - 1000 m deep in granitic rock located in the Canadian Precambrian Shield. Some of the main conclusions from the research program are as follows: 1) Titanium or copper containers are expected to last at least 500 years when in contact with groundwater, which is the period of time that the hazard is greatest. 2) The solubility of uranium oxide is very low when groundwaters are slightly reducing, a result that has been confirmed by examining a natural analogue. 3) Transport of radionuclides away from the containers would be delayed significantly by placing a compacted bentonite layer between the containers and the host rock. 4) Granite plutons contain relatively large rock volumes of low groundwater permeability that could accommodate a vault design that will ensure that radionuclides do not reach the surface in unacceptable concentrations. AECL is also developing a permanent disposal facility for low- and intermediate-level wastes, called the Intrusive Resistant Underground Structure (IRUS). It consists of underground concrete vaults that will contain wastes with hazardous life-times of up to 500 years. Prior to disposal in IRUS, the waste will be processed in the Waste Treatment Center at Chalk River Nuclear Laboratories.

INTRODUCTION

The objective of high-level nuclear waste disposal is to permanently protect the public and the environment from the waste in such a manner that no burden or responsibility would be passed on to future generations. Permanent disposal of high-level nuclear waste in stable geological media is considered by most countries to be a practical and safe disposal method. Research is showing that a number of geological media are suitable and most countries are focussing on the medium that is most appropriate for their circumstances. For example, Canada, Sweden, Finland, and Switzerland are studying granite; West Germany is examining salt; the United States is studying volcanic tuff; and Belgium is studying clay. In each case, a multi-barrier containment system has been adopted in which the intrinsic containment provided by the geologic medium is supplemented by passive engineered barriers such as waste forms having low- solubility, corrosion-resistant containers, buffer systems to reduce corrosion and contaminant transport, and materials to backfill and seal openings.

In Canada, about 15% of our electricity is currently generated by nuclear power using CANDU heavy-water moderated reactors. In addition to the 12.5 GWe installed nuclear capacity, there are 3.6 GWe under construction. Our largest nuclear utility, Ontario Hydro, has recently put forward an expansion plan that could substantially increase their nuclear generation over the next 25 years.

Used fuel is currently produced at a rate of about 1800 Mg(U) per year. The fuel is now being stored in water pools at the nuclear stations, and it is well established that this method is safe and reliable, and could continue for many decades. However, it is recognized that storage is not a permanent solution, and the decision was made in the 1970's that disposal should be the final step in the nuclear fuel cycle. In 1981, the Canadian government approved a ten year generic research and development program to assess the concept of nuclear fuel waste disposal deep in plutonic rock of the Canadian Shield. The results of this generic (non-site specific) research will be reviewed under the Federal Environmental Assessment and Review Process. The Environmental Impact Statement for this review will be submitted by AECL in 1991 for an in-depth scientific and technical review followed by public hearings. No effort relating to screening or selection of potential disposal sites can be initiated until a decision is made by the government following the hearings.

The Atomic Energy Control Board requires that following closure of the disposal vault, no individual should receive an annual radiation dose greater than 0.05 mSv (compared to the 1 mSv received annually from natural sources). It must be shown quantitatively that this criterion can be satisfied for a period of 10 000 years (1).

To meet the safety requirements, we have adopted a passive multi-barrier concept for disposal that combines the structural, hydraulic and geochemical characteristics of the rock mass with a series of engineered barriers to provide effective containment of the waste. The conceptual disposal vault consists of an array of disposal rooms, excavated in plutonic rock at a depth between 500 and 1000 m, covering an area of about 4 km^2 (see Fig. 1). Cylindrical containers of waste would be placed in boreholes in the floor of the disposal rooms and would be surrounded by a compacted mixture of bentonite and sand. An alternative approach would be to place the containers directly into the clay as opposed to using boreholes. Once the rooms were filled,

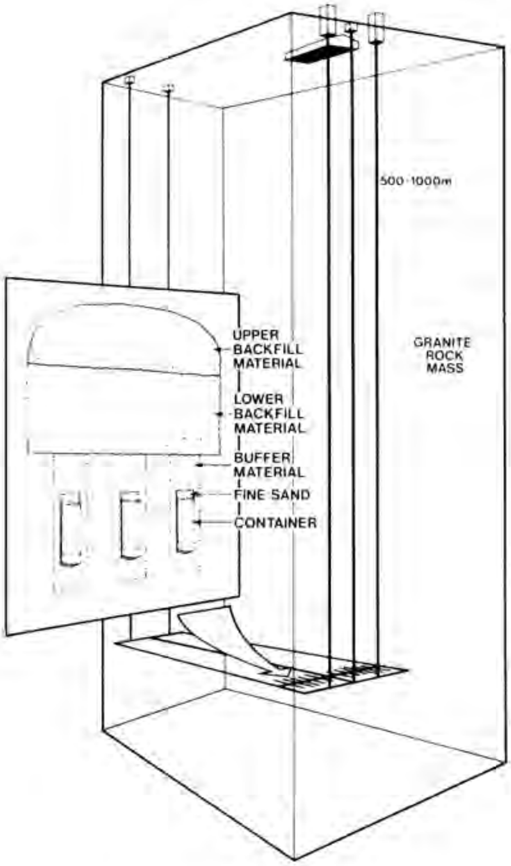

Fig. 1. The Canadian Concept for a Nuclear Fuel Waste Disposal Vault.

they would be backfilled by compacting a mixture of clay and crushed granite in the lower portion of the room and pneumatically filling the top portion with bentonite and sand. Concrete bulkheads would seal the room entrances. Closure of the vault would be achieved by backfilling the access tunnels in the same manner as the rooms. The shafts leading to the access tunnels would be backfilled with compacted clay and crushed granite separated by a series of supporting concrete bulkheads.

RESEARCH AND DEVELOPMENT PROGRAM FOR HIGH-LEVEL WASTES

The Canadian research and development program has three major goals:

1. to develop and demonstrate technology to site, design, build and operate a disposal facility in plutonic rock that will satisfy Canadian regulatory safety criteria,
2. to develop and demonstrate a methodology to evaluate the performance of a disposal system against the safety criteria, and
3. to show that suitable sites in plutonic rock are likely to exist that, when combined with a *suitably designed* facility, would meet the safety criteria.

The following sections discuss how these goals are being addressed.

Fuel Containers

The fuel container design target is to prevent groundwater from contacting the fuel for at least 500 years. Research has focussed on titanium alloys and copper, which are found to be particularly resistant to the chloride-rich groundwaters found deep in the Canadian Shield.

Experiments with titanium alloys have shown that their corrosion rate is less than 1 μm/a under the conditions expected in the disposal vault (groundwater at a temperature less than 150°C, and with a chloride content less than 1 mol/L) (2). This extremely low corrosion rate is due to the formation of a passivating layer on the surface of the metal. If the film breaks down, then localized effects, such as crevice corrosion, could occur. However, electrochemical studies have shown that the propagation of crevices may be prevented by the re- establishment of the protective oxide film. In particular, it has been found that crevice corrosion does not occur at all for ASTM Grade 12 titanium at temperatures less than 70°C. There is little doubt that a 5 mm thick titanium container would isolate the used fuel from groundwater for at least 500 years.

Research has also been carried out on copper, where only uniform corrosion is expected to be important. The dissolution of copper has been characterized in chloride solutions and in the presence of compacted bentonite (3). It is found that the corrosion rate is limited by the rate at which the dissolved metal species are transported away from the corroding surface.

Fuel Behavior

In analyzing fuel behavior in groundwater, it is assumed that the Zircaloy fuel sheath will not be an effective barrier to prevent groundwater from contacting the fuel. The reason for this is that the chloride-rich groundwater may induce crevice corrosion in the sheath. However, it is expected that the UO_2 fuel matrix will provide an effective containment for most of the radionuclides.

Our research has shown that there are three principal mechanisms by which radionuclides could be released from CANDU fuel in groundwaters that are found in the Canadian Shield (4). The first mechanism is the rapid release of about 2% of the cesium and iodine when the fuel sheath fails. The second mechanism is the slow release of iodine and cesium due to preferential dissolution at the grain boundaries. This would account for about 6% of the inventory of these species. Finally, the remaining fission products and actinides trapped within the uranium oxide grains would be released extremely slowly as the grains dissolved.

Once species are released from the fuel, they would encounter reducing conditions in the vault. Experiments with used fuel have shown that uranium concentrations in low to moderately saline groundwaters are about 1 - 10μg/L, and the dissolution rates are found to be extremely low. In addition, it is found that the mobility of some key species such as Tc is restricted due to precipitation as highly insoluble salts.

The stability of uranium oxide in groundwater is being examined at the Cigar Lake uranium deposit in northern Saskatchewan (5). The deposit, which was formed about 1.3 billion years ago, is situated at a depth of 430 m at the interface between the host sandstone formation and the underlying basement rock. The ore body is 2000 m long, 100 m across, and 20 m thick at mid-length. It contains about 150 000 Mg of high-grade ore in the form of individual grains of uranium oxide mixed with clay minerals. The average concentration of the uranium oxide is 12%, although local concentrations as high as 60% have been found. The ore body is surrounded by a clay-rich layer that varies in thickness from 5 to 30 m. The interface between the ore and clay is composed of an iron oxide/hydroxide layer.

Over the past 1.3 billion years, the Cigar Lake deposit has been in contact with groundwater. Investigations have shown that the surface oxidation state of the uranium oxide grains is below U_3O_7 (6). Such oxidation states are consistent with the observed redox conditions of groundwater samples from the ore zone. In addition, laboratory measurements of the dissolution behavior of uranium oxide fuel show that compositions below U_3O_7 result in very low solubility. This is consistent with field measurements that show water samples only 5 m away from the ore body contain uranium concentrations that are below the levels specified for drinking water.

The significance of the above observations require further development of our understanding of the hydrogeology and geochemistry of Cigar Lake. However, it is apparent that conditions exist in nature that result in the immobilization of large quantities of uranium ore whose properties are similar to nuclear waste. The application of our technology to characterize the Cigar Lake observations will increase our confidence in the tools and methods that will be used to assess the performance of a waste vault.

Sealing and Backfilling Materials

Our research is showing that radionuclide movement in the compacted bentonite- sand mixture that surrounds the waste containers is limited by diffusion (7). For example, layer thicknesses of only 25 cm can delay movement of dissolved and suspended radionuclides for thousands of years. Laboratory data have shown that bentonite clay is expected to remain stable for long periods of time under the geochemical conditions in the Canadian Shield. Field and laboratory studies of natural bentonite deposits in southern Saskatchewan have confirmed that bentonite has maintained an acceptably high swelling potential and low permeability millions of years after its deposition (8). The mechanically compacted clay backfilling materials for the disposal rooms have properties that are similar to the buffer materials, and provide the potential for diffusion rates of the order of thousands of years per meter.

Geological Medium

In Canada, plutonic rock is favored as it allows the greatest scope for the application of technical, social, political, and economic factors to the selection of the eventual disposal site. Also, many of the plutons in the Shield are not associated with economic mineral deposits. Therefore, mineral exploration of such plutons is expected to be low in the future and accidental intrusion into the vault is highly unlikely.

Since Ontario has the largest nuclear program in Canada, it is likely that the first disposal vault would be located in that province. In Ontario, the Canadian Precambrian Shield extends over more than 600 000 km^2, and more than 1300 plutons have been identified by the Geologic Survey of Canada. Moreover, the largest area of the Shield in Ontario, the Superior Structural Province, has not had major orogenic activity for 2500 million years. Our field, laboratory, and theoretical research programs indicate that underground excavations in good quality plutonic rock are stable and should experience very low time-dependent deformations during the minimum design life of the containers (500 years).

Hydrogeological testing in our field research areas is showing that the natural driving forces for groundwater flow deep in plutonic rock may be low as a result of low regional topographic gradients. Therefore, it may be possible to find regions in the Shield where transport of any radionuclides that escape from the engineered barriers would be inhibited by very slow groundwater flow. Furthermore, there are large volumes of plutonic rock with extremely low porosity and permeability, which would limit the access of groundwater to the waste.

We are developing the methodology to characterize plutonic rock masses and have been applying it to our field research areas, particularly the Lac du Bonnet Batholith (9). This is a large granite pluton, located in the Whiteshell region of southern Manitoba, which is similar to those found throughout the Canadian Shield. The pluton was intruded over 2500 million years ago into the rock formations existing at the time. Field research has been ongoing at this site over the past 10 years. The methodology we have developed to derive a conceptual model of a pluton has four main steps:

1. Airborne measurements of magnetic and density variations are performed to define the boundaries of the pluton. The surface of the site is carefully examined to identify any features that are the surface expression of faults and fracture zones in the underlying rock. At selected locations, seismic and electromagnetic waves are transmitted from the surface into the underlying rock to determine the presence and orientation of fracture zones.
2. Guided by the results of the surface studies, cored holes are bored into the rock mass at selected locations to depths up to 1000 m. Core samples are examined, along with the interior surface of the holes, to obtain information on the distribution of fractures within the rock mass. Normally, it is found that the fracturing is concentrated in narrow zones (about 1 m thick) that are hydraulically active. Steel casings fitted with valves and sealing systems are inserted into the holes to isolate these fracture zones and allow the hydraulic properties of the zones to be monitored. Chemical analysis of water samples from the fracture zones provides information on the origin of the water.
3. The isolated zones within the boreholes are used to determine the interconnections between fracture zones and the hydraulic properties of the interconnecting flow paths. This is done by either injecting or withdrawing water from an isolated zone while monitoring isolated zones in neighboring boreholes. By repeating this procedure at a number of isolated zones, the three-dimensional characteristics of the flow paths, and their hydraulic characteristics, can be determined.
4. Finally, the predictions from a three-dimensional model (MOTIF) for describing water movement are compared to data on natural flow in the network of isolated zones (10, 11). Refinements are made in both the model and the description of the flow paths until agreement is attained. The model then provides a basis for analyzing the containment potential of the rock mass.

Underground Research Laboratory

The Underground Research Laboratory (URL) has been constructed to perform large- scale, in situ experiments in plutonic rock that is representative of the rock being considered for a waste vault in Canada. The laboratory has been developed in a previously undisturbed granitic pluton, the Lac du Bonnet Batholith, that was characterized thoroughly before, and during, construction. The general objectives of the URL program are to provide realistic environment and boundary conditions for understanding integrated processes, to examine scaling effects, to conduct long-term experiments on a scale that is impracticable in the laboratory, and to provide a database for model development and validation.

Currently, the URL consists of a 443 m shaft, shaft stations at 130 m, 300 m, and 420 m, and a working level at 240 m. A core program consisting of 9 experiments has been established for the URL at the 240 m and 300 m levels (Table I).

TABLE I

Underground Research Laboratory Core Program

Experiment	Description	Completion
1	Solute Transfer in H.F. Rock	1995
2	Solute Transfer in M.F. Rock	1995
3	Buffer/Container	1994
4	Grouting	1996
5	Shaft Sealing	2000
6	Multicomponent	2000
7	Mine-By	1995
8	Characterization	1998
9	In Situ Stress	1997

The first two studies indicated in Table I involve solute transport. The study of solute transport in highly fractured rock provides data on the dependence of transport mechanisms on mechanical changes in the fracture zones. The experiments will involve tracer tests to elucidate the scale dependence of porosity and dispersivity, and tests to measure the compressibility, porosity, and permeability of a highly fractured rock zone. Both sets of tests are currently underway. The study of solute transport in moderately fractured rock will assess the validity of using equivalent porous media transport properties to model activity transport.

The next four experiments in Table I (#3-#6) pertain to vault sealing. The buffer container experiment will demonstrate the engineering aspects of borehole emplacement, and will provide a database to verify integrated models describing processes occurring in the rock mass and buffer due to the addition of moisture and heat. The test emplacement borehole will contain an electrically heated container enclosed in a highly compacted sodium bentonite clay/sand buffer. Instrumentation will be installed to monitor the rock, buffer, and container. The grouting experiment is an engineering demonstration of a grouted fracture zone. We will develop and assess the performance of grouting materials, equipment, and emplacement methods for grouting fine fissures and zones of fractured rock. The shaft sealing experiment will be done to demonstrate the methodology for, and the performance of, our sealing concept. A multicomponent shaft seal comprising a concrete plug, grout, and a clay/sand backfill will be studied. The sixth experiment will be a multicomponent test to examine the room backfilling aspects of the disposal concept, and to obtain a database on the performance of a fully backfilled room under the influence of moisture and heat.

The mine-by experiment, #7, will examine the impact of excavation on the geosphere. This experiment, scheduled to begin this year, will study the material properties and behavior of rock during vault construction activities, and will also assess the viability of the borehole emplacement concept. Prior to the initiation of the integrated experiments, component experiments are being done in the URL to characterize the response of a rock mass and water bearing fracture during excavation, the permeability in an excavation damage zone, and the performance of acoustic emission/microseismic monitoring to assess rock response to excavation.

The final two experiments (#8, #9) involve characterization of the disposal vault and monitoring methods. The objective of the URL characterization program is to develop and demonstrate a methodology for underground characterization, and to provide the conceptual model of the hydrogeological, hydrogeochemical, geological and geomechanical environment around the URL. This activity, which has been ongoing since the URL site characterization work began, is generating data for model development and provides essential information for the interpretation of experiments. The in situ stress program is designed to develop and demonstrate tools and instruments to improve the calculation of stresses from field data, and to determine the influence of various physical factors on the calculated stress. It is interesting to note that the analysis of field data from stress measurements has proven to be challenging, since the rock below the 240 m level in the URL is responding in a non-linear and non- elastic fashion.

LOW- AND INTERMEDIATE-LEVEL RADIOACTIVE WASTES

Low and intermediate-level radioactive waste (LILW) production in Canada is about 11 000 m^3 per year (before processing), and arises from nuclear generating stations, universities, hospitals, R&D institutes, and the nuclear fuel industry (12-15). Atomic Energy of Canada Limited, the nuclear utilities, and mining companies have programs to manage their LILW. In addition, AECL accepts wastes from radioisotope producers and users, on a commercial basis.

Ontario Hydro operates a centralized facility at the Bruce Nuclear Power Development site for processing and storing LILW from Ontario Hydro reactors. The storage methods at Bruce are 1) shallow, in-ground, reinforced concrete trenches, 2) vertical, concrete tile holes backfilled with concrete, 3) above- ground concrete "quadricells", and 4) low-level waste storage buildings. The appropriate storage method is selected according to the physical/chemical characteristics of the waste and its level of radioactivity.

AECL operates similar storage facilities at its Chalk River Nuclear Laboratories (CRNL), and is now developing the technology for permanent disposal. The intrusion-resistant underground structure (IRUS) at CRNL will be a prototype system for disposal of LILW having hazardous life-times up to 500 years (16-18). The design is based on an underground concrete vault concept. Construction of the facility will begin in 1990. Before waste is delivered to IRUS, it will be characterized and processed in the Chalk River Waste Treatment Center. Liquid wastes will be treated using microfiltration and reverse osmosis to separate radionuclides from solution. The separated waste material will then be mixed with emulsified bitumen and simultaneously heated to drive off the water. Finally, the bitumen/waste product will be sealed in steel drums. Solid wastes can either be incinerated and the resulting ash bituminized, or they can be baled.

IRUS will consist of three reinforced concrete vaults, each of which is 30 m long, 20 m wide, and 9 m deep. While the vaults are operating, they will be covered by an unheated, weather-resistant metal frame building. Waste emplacement and backfilling operations will be facilitated using an overhead crane. One vault will have a capacity for 2 000 m^3 of packaged waste in the form of compacted bales, 200-litre steel drums, or boxes of unprocessed wastes. Spaces between the waste packages will be filled with sand to facilitate waste stacking. The vault floor will consist of a compacted layer of clay and sand to act as a buffer to retard radionuclide migration. Once the vault has been filled, it will be covered by a concrete cap and a 1.5 m thick layer of sand and soil. Vegetation will prevent the erosion of the sand and soil layer. The crane, building and other equipment/services will be moved to additional IRUS units.

IRUS will replace the current strategy of LILW interim storage with permanent disposal. Moreover, it is expected that the costs associated with permanent disposal in IRUS will be comparable to the current cost of engineered storage.

CONCLUSIONS

The Canadian Nuclear Fuel Waste Management program includes elucidation of the basic chemistry and physics associated with engineered and natural barriers, large-scale in situ experiments, the characterization of natural analogues such as uranium oxide and bentonite deposits, and extensive geological field work. This research is giving us confidence that it will be possible to identify a large number of locations in the Canadian Shield that, after detailed characterization, will meet the safety requirements.

The LILW disposal strategy is well-developed, and the new IRUS facility at CRNL will provide AECL with an effective means to permanently dispose of low- and intermediate-level wastes.

REFERENCES

1. Atomic Energy Control Board, "Regulatory Objectives, Requirements and Guidelines for the Disposal of Radioactive Wastes - Long Term Aspects," Atomic Energy Control Board Regulatory Document, R-104 (1987).
2. B.M. IKEDA and C.F. CLARKE, "Titanium Corrosion under Canadian Nuclear Waste Disposal Conditions," Proc. 2nd International Conference on Radioactive Waste Management, Winnipeg, Canadian Nuclear Society, p. 605 (1986).
3. F. KING and C.D. LITKE, "The Corrosion Behavior of Copper under Simulated Nuclear Fuel Waste Disposal Conditions," Proc. 2nd International Conference on Radioactive Waste Management, Winnipeg, Canadian Nuclear Society, p. 593 (1986).
4. L.H. JOHNSON, D.W. SHOESMITH, and S. STROES-GASCOYNE, "Spent Fuel: Characterization Studies and Dissolution Behavior under Disposal Conditions," Scientific Basis for Nuclear Waste Management Vol. XI, Pittsburgh, MRS (M. ATED and R. WESTERMAN, Ed.), p. 99 (1988).
5. J.J. CRAMER, "A Natural Analog for a Fuel Waste Disposal Vault," Proc. 2nd International Conference on Radioactive Waste Management, Winnipeg, Canadian Nuclear Society, p. 697 (1986).
6. S. SUNDER, P. TAYLOR, and J.J. CRAMER, "XPS and XRD Studies of Uranium Rich Minerals from Cigar Lake, Saskatchewan," Scientific Basis for Nuclear Waste Management, Vol. XI, Pittsburgh, MRS (M. ATED and R. WESTERMAN, Ed.), p. 465 (1988).
7. C.H. CHEUNG, "Evaluation of Methodologies for Determining Ionic Diffusion Coefficients in Clays," Proc. of the Canadian Engineering Centennial Convention, Montreal, p. 195 (1987).
8. D.W. OSCARSON, D.A. DIXON, and M.N. GRAY, "Swelling Capacity and Permeability of an Unprocessed and Processed Bentonite Clay, Journal of Eng. Geology (in press).
9. K.W. DORMUTH, W.T. HANCOX, *and* S.H. WHITAKER, "Geological Considerations for Disposal of Nuclear Fuel Wastes in Canada," Proc. 28th International Geological Congress, Washington (1989) (in press).
10. V. GUVANASEN, "Development of a Finite-Element Code and Its Application to Geoscience Research," TR-299*, Atomic Energy of Canada Limited Technical Record, p. 554 (1985).
11. C.C. DAVISON, T. CHAN, and N.W. SCHEIER, "Experimental Activities of the Canadian Nuclear Fuel Waste Management Program to Validate Geosphere Models," Proc. Geoval-87, Stockholm, p. 401 (1987).
12. M.A. Feraday, "Canadian Experience with the Storage and Disposal of Low- and Intermediate-Level Wastes," Proc. 3rd Symp. on Low-Level Waste Disposal, NUREG/CP-0028, Vol. 3, p. 411 (1983).
13. T.J. Carter, "Radioactive Waste Management Practices at a Large Canadian Electrical Utility," Radioactive Waste Management, 2, 4, p. 381 (1982).
14. D.H. Charlesworth and T.J. Carter, "Low- and Intermediate-level Radioactive Waste Management in Canada," Proc. Int. Conf. on Radioactive Waste Management, Winnipeg, Canadian Nuclear Society, p. 242 (1982).
15. J.E. LeSurf, D.H. Charlesworth and H.N. Isaac, "Processing, Storage, and Disposal of Low- and Intermediate-Level Waste in Canada," Waste Management '84, Tucson, Vol. 2, p. 437 (1984).
16. D.G. Hardy and D.F. Dixon, "Safety and Cost Assessments for Disposal in a Prototype Shallow Land Burial Facility," Proc. Intl. Conf. on Radioactive Waste Management, Winnipeg, Canadian Nuclear Society, p. 418 (1986).
17. K.E. Philipose, "500-Year Concrete for a Radioactive Waste Repository," Proc. Waste Management '88, Tucson, Vol. 1, p. 995 (1988).
18. J.S. Devgun and S.R. Wilkinson, "Long-Term Predictions of Water Table from Precipitation Analysis for a Waste Disposal Site,," Proc. Waste Management '88, Tucson, Vol. 2, p. 775 (1988).

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