Technical Research and Development Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2008

NWMO TR-2009-01 **March 2009**

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Nuclear Waste Management Organization

nwmo
NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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ABSTRACT

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Author(s): E. Kremer, M. Ben Belfadhel, K. Birch, J. Freire-Canosa, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, A. Khan, G. Kwong, T. Lam, H. Leung, P. Lum, P. Maak, S. Russell, K. Sedor, E. Sykes and A. Vorauer
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Abstract
This report is a summary of progress in 2008 for the Nuclear Waste Management Organization's (NWMO's) technical research and development (R&D) program. The technical R&D program is supporting implementation of Adaptive Phased Management, Canada's approach for long-term management of used nuclear fuel.

Significant technical program achievements in 2008 include:

- NWMO participated in several research and demonstration projects in geoscience, safety assessment and repository engineering at the SKB Äspö Hard Rock Laboratory (HRL) in Sweden.
- NMWO joined the Mont Terri Project as a partner. This underground research laboratory in Switzerland is located in sedimentary rock and complements NWMO's participation in the Äspö research laboratory in crystalline rock.
- NWMO joined the Greenland Ice-Sheet Hydrology Project in collaboration with SKB, Posiva, the Geological Survey of Greenland and Denmark, the Geological Survey of Finland, the University of Indiana, and the University of Waterloo.
- NWMO joined Atomic Energy of Canada Limited (AECL), SKB (Sweden), Posiva (Finland), and Andra (France) in a cooperative project for monitoring the performance of a full-scale low-permeability shaft seal at the AECL Underground Research Laboratory in Manitoba.
- NWMO presented/published technical papers in several international conferences/journals covering used nuclear fuel in dry storage and corrosion of container materials.
- The NWMO Independent Technical Review Group (ITRG) held their first meeting with NWMO staff and later presented their review findings in a 2008 report to the NWMO Board of Directors and Advisory Council. NWMO will prepare an action plan in 2009 to address the recommendations of the ITRG report.
- Methods were identified for used-fuel container placement in a deep geological repository. The preferred methods for further conceptual development are (i) in-floor borehole placement in crystalline rock, (ii) horizontal tunnel placement in either hard or soft sedimentary rock, and (iii) horizontal borehole placement in soft sedimentary rock.
- A technical report was completed that describes the Copper Corrosion Model for copper used fuel containers in sedimentary rock.
- A state-of-the-science review was completed on the effects of hydrogen gas on suppressing used fuel dissolution in a deep geological repository.

- Microbial analyses of samples of deep limestone and shale samples under various groundwater salinities indicated microbial viability became limited at even lower salinities than previous studies.
- A state-of-the-science review of airborne and surface-based site evaluation techniques for screening potential candidate sites was completed, as well as a compilation of geoscientific information on the four nuclear provinces.
- A state-of-the-science review of sorption under saline conditions was completed.
- Significant additional data were obtained on iodine transfer factors in a variety of plant and animal species including data for species of importance to hunting lifestyle.
- NWMO was approved by the Natural Sciences and Engineering Research Council for the Industrial R&D Scholarship and Fellowship program for the joint funding of postgraduate and postdoctoral students.
- NWMO obtained concurrence of the Canadian Nuclear Safety Commission (CNSC) staff on putting a protocol agreement on the regulatory interface in place during the pre-licensing phase of Adaptive Phased Management.
- The annual NWMO Technical R&D Program Update was provided to CNSC staff in Ottawa.
- NWMO background papers and information sheets were prepared to support development of the siting process. NWMO technical staff participated in several workshops and projects to help build their awareness or understanding of Aboriginal Traditional Knowledge.

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1. INTRODUCTION

The NWMO's research and development (R&D) program is supporting implementation of Adaptive Phased Management (NWMO 2005), the approach selected by the Government of Canada in 2007 for long-term management of nuclear fuel waste.

Adaptive Phased Management (APM) has the following characteristics:

- centralized containment and isolation of the used fuel in a deep geological repository in a suitable rock formation, such as crystalline rock or sedimentary rock (see Figure 1.1);
- flexibility in the pace and manner of implementation through a phased decision-making process, supported by a program of continuous learning, research and development;
- optional step in the implementation process in the form of shallow underground storage of used fuel at the central site prior to final placement in a deep repository;
- continuous monitoring of the used fuel to support data collection and confirmation of the safety and performance of the repository; and
- potential for retrievability of the used fuel for an extended period, until such time as a future society makes a determination on the final closure, and the appropriate form and duration of postclosure monitoring.

A summary of progress in 2008 for the NWMO's technical R&D program for long-term management of Canada's used nuclear fuel is described in this Annual Technical Report.

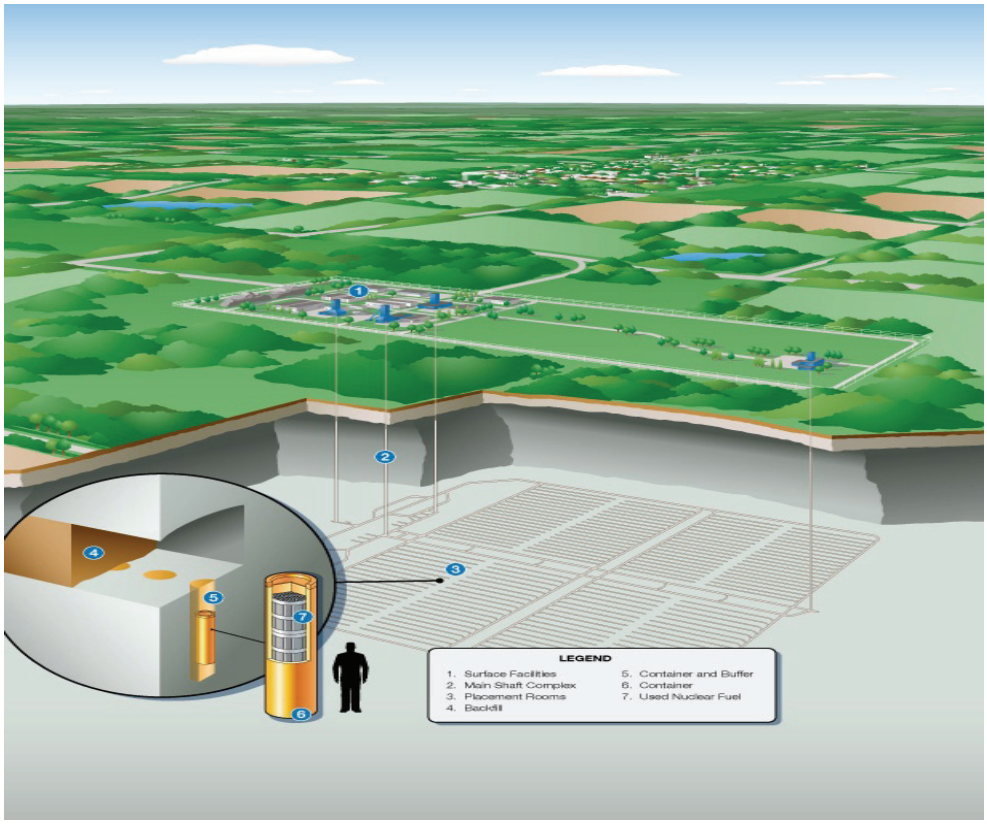


Figure 1.1: Conceptual Design of a Deep Geological Repository for Used Nuclear Fuel

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 REGULATORY FRAMEWORK

Nuclear facilities, including those for long-term waste management such as a deep geological repository, are regulated by the Canadian Nuclear Safety Commission (CNSC), under the *Nuclear Safety and Control Act*. Pursuant to regulations under this *Act*, licences are required from the CNSC for all phases of a project - site preparation, construction, operation, decommissioning, and abandonment. The CNSC provides additional guidance through regulatory policies, standards and guides.

In 2004, the CNSC published Regulatory Policy P-290, *Managing Radioactive Waste*. Central to the policy is the recognition that nuclear substances are subject to the *Nuclear Safety and Control Act* and its regulations. This means that used fuel is subject to all of the requirements of nuclear safety, security and safeguards embodied in the *Act* and the associated Regulations.

Regulatory Policy P-290 further states the following principles:

- minimisation of waste generation;
- management commensurate with the hazard;
- assessment of future impacts to encompass the time of maximum predicted impact;
- predicted impacts no greater than the impacts that are permissible in Canada at the time of the regulatory decision;
- measures for safe management to be developed, funded and implemented as soon as reasonably practicable, and
- trans-border effects no greater than the effects experienced in Canada.

In 2006, the CNSC issued Regulatory Guide G-320, entitled *Assessing the Long Term Safety of Radioactive Waste Management*. The Guide describes approaches for assessing the potential long term impact that radioactive waste storage and disposal methods may have on the environment and on the health and safety of people.

The application for a CNSC licence for a deep repository for used nuclear fuel would trigger an Environmental Assessment (EA) under the Canadian Environmental Assessment Act (CEAA). Under the CEAA, an EA is required to assess the environmental effects of most projects requiring federal action or decisions.

Public input will be required at appropriate stages in the EA and licensing process.

2.2 TECHNICAL PROGRAM OBJECTIVES

A strong technical R&D program will ensure that NWMO will benefit from technological innovation in radioactive waste management developed in Canada and abroad, and will ensure that the NWMO maintains adequate human resources to manage the various phases of implementing Adaptive Phased Management.

The principal objectives of the NWMO's technical R&D program are:

i. Maintain skilled technical capability by developing in-house expertise and effective working relationships with Canadian universities and the consulting community.

ii. Enhance scientific understanding of the technology for central storage and long-term containment and isolation of used fuel in a deep geological repository.

iii. Further develop capability to evaluate potential sites from a technical perspective.

iv. Seek opportunities for international collaboration and participation in joint technical research, and development and demonstration programs, to bring the best international knowledge and practices into the technical work of the NWMO.

v. Build understanding of monitoring and retrievability during the various stages of implementation.

vi. Maintain awareness of alternative means for the long-term management of used nuclear fuel.

vii. Revise and update the conceptual design and cost estimate for long-term management of Canada's used nuclear fuel.

viii. Build understanding of the process to interweave Aboriginal Traditional Knowledge with western science during implementation.

The technical R&D program is described in more detail in the following sections of this Annual Technical Report.

A list of the technical reports produced in 2008 is provided in Appendix A.1. All technical reports published before 2000 are listed in Garisto (2000), while the 2000 to 2007 reports are listed in corresponding annual progress reports (Gierszewski et al. 2001, 2002, 2003, 2004a; Hobbs et al. 2005, 2006; Russell et al. 2007; Birch et al. 2008). Note that prior to 2007, the technical program was managed by AECL and then by Ontario Power Generation.

Appendix A.2 provides a list of the papers and presentations made by technical program staff and contractors.

Appendix A.3 provides a list of postgraduate theses prepared for the technical work program.

Appendix A.4 provides a list of the primary external contractors and collaborators for the technical work program.

Abstracts of all reports produced by this program in 2008 are included in the final part of this Annual Technical Report (Appendix B).

2.3 INTERNATIONAL ACTIVITIES

An important part of the NWMO's technical R&D program is interacting with the corresponding national radioactive waste management organizations in other countries. The NWMO has developed formal agreements with SKB (Sweden), Posiva (Finland), Nagra (Switzerland) and Andra (France) to exchange information arising from their respective programs on nuclear waste management. These countries are developing used fuel repository concepts that are similar to the Canadian concept, and their programs are advanced with respect to repository siting, design development and approvals.

Since 2004, Canada has been participating in experiments at the SKB Äspö Hard Rock Laboratory (HRL). The purpose of this participation is to improve our understanding of key processes in a repository through working on large-scale projects, and to directly share lessons learned in repository technology development and site characterisation.

In 2008, NWMO and its expert consultants participated in the Colloid Dipole Experiment, the LASGIT Gas Injection Test, and the Engineered Barrier System Modelling Task Force and Groundwater Modelling Task Force groups. Support was also provided with respect to the Long-term Test and Canister Retrieval Tests, the ROSE (rock-shear) test design, and the BACLO (backfill) project.

In 2008, NWMO became a participating partner in the Mont Terri Project and is actively involved in underground experiments in sedimentary rock covering rock stress, excavation stability, gas transport through clay seals and rock formations, container corrosion, groundwater monitoring and microbial activity.

NWMO continues to participate in the international radioactive waste management program of the OECD Nuclear Energy Agency (NEA). Members of this group include all the major nuclear energy countries, both waste owners and regulators. This group co-ordinates several activities.

NWMO also supported BIOPROTA, the international working group on biosphere modelling.

3. REPOSITORY ENGINEERING

The main objectives of the repository engineering program are: to develop the engineering data, models, methods and tools necessary to develop conceptual designs for a deep geological repository and associated systems; to provide engineering input to assess the safety of the deep geological repository concept; to support planned site characterization and investigation activities; and to support the development of cost estimates for long-term management of Canada's used nuclear fuel.

In the following sections, the status of the repository engineering program and the achievements in 2008 are outlined for work activities related to the development of used fuel integrity, container corrosion, repository sealing material development and repository design.

3.1 USED FUEL INTEGRITY

The NWMO continued to advance knowledge that supports the current assumption that used CANDU fuel may remain in dry storage for a period of time of the order of 100 years without significant deterioration to its mechanical properties and structural integrity. Maintenance of fuel bundle integrity is important to ensure the safety and efficiency of post-storage operations such as the handling and transportation of the fuel bundles to a deep geological repository.

The NWMO's Used Fuel Integrity Program is an integrated program with the primary objective of demonstrating that the structural integrity of used (spent) CANDU fuel bundles will be preserved during their storage in a dry mode. A Standard CANDU fuel bundle[1] is shown in Figure 3.1. A number of studies assessing various postulated mechanisms that could lead to fuel degradation concluded that Delayed Hydride Cracking (DHC) of the fuel bundle endcap/endplate welds presented the highest risk to the structural integrity of the CANDU fuel bundle during long-term dry storage.

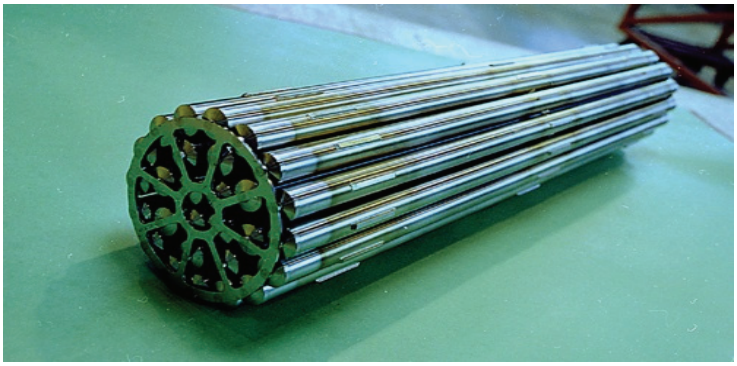


Figure 3.1: A Standard CANDU fuel bundle (0.495 metres in length, holding 19.2 kg of uranium)

[1] Ontario Power Generation and Bruce Power have also been using Long CANDU fuel bundles in their reactors. The Long bundle is 0.508 m in length, holding 19.2 kg of uranium.

Key to understanding the susceptibility of the endcap/endplate welds to DHC is having a well-defined mapping of the stress fields in this area of the CANDU fuel bundle. Consequently, a finite element model of the fuel bundle known as the Bundle Stress Model was developed to estimate the stress fields in the bundle as a result of typical deformations. Data on deformations are obtained through post-irradiation examinations (PIE) of the bundles after their in-reactor-life.

The Used Fuel Integrity Program consists of the following activities:

1. Complete development of a Bundle Stress Model.
2. Studies to assess the susceptibility of the CANDU fuel bundle endcap/endplate welds to DHC.
3. Determining the thermal behaviour of the Ontario Power Generation Dry Storage Containers (DSCs) during processing and storage and to perform a thermal analysis of the DSC.
4. Complete participation in the IAEA SPAR II (Spent Fuel Performance and Research) - Coordinated Research Project (CRP) on Dry Storage of Spent Fuel.

3.1.1 Bundle Stress Model Verification and Sensitivity Analysis

Development of the Bundle Stress Model as a finite element model using the ANSYS platform to predict the stress fields in the fuel bundle was completed in 2007. Testing of the Bundle Stress Model to verify its reliability continued during 2008. Earlier results of the testing completed in 2007 on non-irradiated Pickering and Bruce fuel bundles showed the model to adequately predict bundle behaviour primarily in the linear elastic regime relevant to dry storage of the fuel bundles. However, the model tends to overpredict fuel element deformations when the bundle is subjected to mechanical loads. Conversely, it underpredicts the deformations experienced by the endplates under the same loads.

Pull, push and centre load tests were applied to a fuel element or group of fuel elements in the bundles and the deformation of the fuel element most affected by the loads was recorded by means of LVDTs (Linear Voltage Differential Transducers). The loads applied to the bundles covered the linear and plastic regimes. From the point of view of dry storage, there are no driving forces that could lead to bundle deformation in the plastic regime. However, by doing testing in the plastic regime, the capability of the model is better observed. The development of the Bundle Stress Model was reported at the ASTM Conference at Denver, Colorado (Lampman, et al., 2008) and the presented paper accepted for publication in the Journal of ASTM International (Lampman et al., 2009).

Further testing and development of the Bundle Stress Model was conducted in 2008. The main objective was to verify the model and to assess its sensitivity to differences in the fuel bundle manufacturing process by different vendors. After completion of the testing on the non-irradiated fuel bundles in 2007, it was felt that the observed discrepancies between the stress model and the tests might be due to several factors, including lack of sufficient detail in the model on pellet-to-pellet contact in the fuel elements and differences in the material properties assumed at the endcap/endplate welds.

In order to eliminate some of the postulated factors that could contribute to the observed discrepancies, testing was simplified to having a fuel element with some endplate tested by itself on a modified testing apparatus. The results of this test, however, confirmed that the

observed discrepancies between the model predictions and the bundle deformations measured in the testing done in 2007 were valid.

Testing of the model is proceeding to assess whether differences in the dimensions of fuel bundle manufactured components such as the size of the endcap have a significant impact on the bundle model predictions. This sensitivity analysis of the Bundle Stress Model to manufacturing details is targeted for completion in 2009.

3.1.2 Susceptibility of CANDU Fuel Bundles Endcap/Endplate Welds to Delayed Hydride Cracking

During 2008, the work completed in 2007 on the development of a Test Apparatus and Methodology to assess the susceptibility of CANDU fuel bundle endcap/endplate welds to DHC was presented at the 10th International CNS Conference on CANDU Fuel held in Ottawa in October (Shek et al, 2008).

A proposal was also prepared to further expand the non-irradiated endcap/endplate testing to take into consideration variations in bundle types (28- and 37-element bundles), as well as potential manufacturing differences from the two manufacturers supplying CANDU fuel bundles to the Canadian nuclear reactors (General Electric and Zircatec). The planned work will also assess how weld morphology affects the K_{IH} factors. This planned work is expected to begin in 2009.

Results from this work, coupled with predictions for K_{IH} values at the endcap/endplate welds obtained from the Bundle Stress Model, will provide information on whether DHC of the endcap/endplate welds is a concern for dry storage.

3.1.3 Temperature Monitoring of a Dry Storage Container

A DSC was instrumented with 32 thermocouples to measure temperatures at key locations in the DSC, such as the inner liner, the outer C-steel shell, and the DSC lid. The container was then loaded with 384 sixteen-year-old CANDU fuel bundles from Bruce Power's Bruce B station.

Temperature measurements were recorded during key steps of the DSC manufacturing process. Later, after being loaded with fuel, temperatures were recorded during processing activities that included welding of the DSC lid to its base and vacuum drying of the used fuel inside the DSC. Finally, temperatures were also recorded during storage of the DSC at its destination location in the Dry Storage Facility at OPG's Western Waste Management Facility located on the Bruce Site.

The maximum temperature recorded during the summer of 2007 in the inner liner of the DSC was less than 55^0C. The outside ambient air temperature was 30^0C at the time.

A thermal analysis of the DSC using the recorded data is planned using the heat of decay of the stored fuel bundles.

3.1.4 Participation in the IAEA SPAR II on Dry Storage of Spent Fuel

The NWMO participation with the IAEA SPAR II (Spent Fuel Performance and Research) - Coordinated Research Project (CRP) on the Dry Storage of Spent Fuel came to a conclusion in Budapest on June 10-15, 2008. Results of the NWMO Used Fuel Integrity Program were presented to participating countries. The NWMO also provided input to sections of the IAEA technical document on dry storage developed by SPAR II, expected to be published in 2009.

The main concern among the participating State Members was over the impact that Delayed Hydride Cracking may have on the long term behaviour of spent fuel, particularly for high-burnup fuel.

Issues relating to fuel behaviour and integrity during long-term storage and post-storage operations, including handling and transportation, could be considered within the planned scope of work for SPAR.

3.2 CONTAINER CORROSION

3.2.1 Copper Corrosion

The schematic diagram of a copper used-fuel container is shown in Figure 3.2. Copper corrosion work in 2008 focused on investigating stress corrosion cracking (SCC) of copper. The objectives of these experiments are to improve the current knowledge of the copper SCC in repository environment and to determine the boundaries for the environmental parameters affecting SCC of copper. Specific experiments were carried out to examine the effect of high chloride concentration on the SCC behaviour of copper. The findings indicated that a high concentration of 5.5 mol.L-1 NaCl (sodium chloride) would suppress SCC of copper in nitrite, ammonia and acetate solutions (Ikeda and Litke 2008). The high NaCl concentration would suppress SCC by promoting uniform corrosion and disrupting oxide film formation on the crack surface. Specific experiments were performed to investigate the effect of NaCl concentration, aeration and applied current and extension rate on the SCC behaviour of copper in a pH 9 acetate solution. The experimental results indicate that SCC was not observed in a range of acetate concentrations between 0.15 and 0.5 mol.L-1 (Litke and Ikeda 2008).

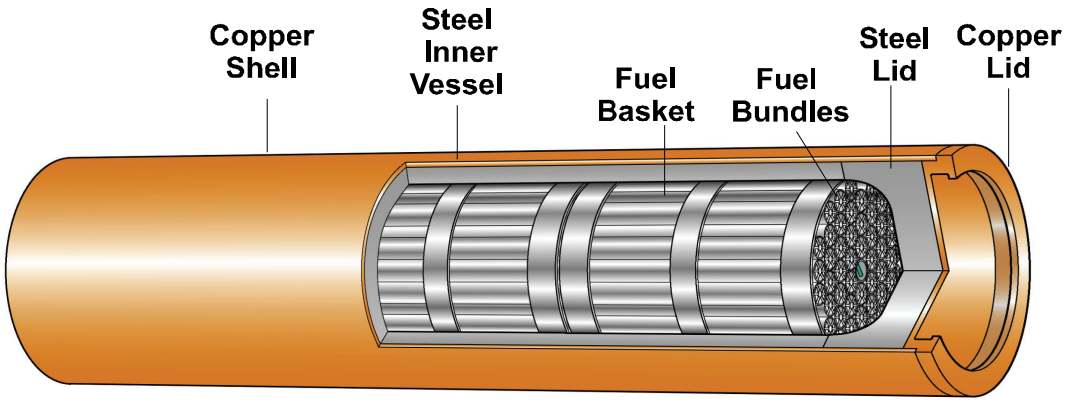


Figure 3.2: Copper used fuel container

The theory manual of a mechanistic based model for the uniform corrosion of copper used fuel container in a deep geological repository in sedimentary rock has been developed (King 2008). The mechanism accounts for all of the important processes involved the corrosion of copper in porous media in contact with oxygen-containing chloride solutions.

3.2.2 Steel Corrosion

In 2008, potential hydrogen-related damages to carbon steel used-fuel containers and their relevance under a repository environment were assessed based on literature findings. The assessment focused on the behaviour of modern steels and the yield stress / threshold hydrogen concentration relationship developed by Japan (JNC 2000) for older carbon steel. In addition, a mixed-potential corrosion model with specific consideration of the interaction of Fe(II) with bentonite, via sorption and precipitation processes was developed. Model developments which include (i) specification of the reaction scheme; (ii) definition of mass balance equations for each species in the model; (iii) specification of initial and boundary conditions of each species including electrochemical expressions at the container surface for electroactive species; and (iv) literature review results and analysis for each process in the model; are documented in details in a theory manual.

In addition to the above, laboratory studies on the anaerobic corrosion behaviour of carbon steel in humid conditions, but not submerged in aqueous solution, were also conducted at the University of Toronto. Experiments began in early 2008 after specially designed corrosion cells were built. Initial tests monitored the hydrogen evolution in a humid environment, at 75% - 100% relative humidity (RH) and 30°C, using a high sensitivity pressure gauge system. Hydrogen was confirmed by a solid-state potentiometric hydrogen sensor which has the capability of detecting hydrogen partial pressure as low as 10^{-6} bar or a corrosion rate of 1.5 x 10^{-4} $\mu m.a^{-1}$. Preliminary results indicate that a corrosion rate as high as 0.2 $\mu m.a^{-1}$ can be sustained for steel coated with salt at 100% RH. Higher corrosion rates (as high as 0.8 $\mu m.a^{-1}$) were obtained in less humid environment (71% RH). Without a salt deposit, pickled steel in humid environment (as high as 100% RH) also showed detectable corrosion for a period up to 800 hours, during which 0.8 kPa of hydrogen was accumulated prior to the apparent arrest of corrosion, representing a metal loss of 3 nm. This corrosion work will continue in 2009. Results of this program will be useful in predicting long-term carbon steel corrosion behaviour, lifetime predictions of carbon steel used-fuel containers and improving the current knowledge of hydrogen gas evolution in a deep geological repository for nuclear waste.

3.3 SEALING MATERIAL DEVELOPMENT

In 2008, the NWMO continued to assess the properties of bentonite-based sealing materials through several laboratory studies, including microbial studies and a consolidation and triaxial laboratory testing program. The focus of many of the studies was on the effect of saline porewater on the sealing materials characteristics and microbial viability. These tests were carried out on the following sealing materials that are being considered for use in a deep geological repository to encapsulate the used fuel canister; (i) highly compacted bentonite (HCB) – 100% bentonite clay; (ii) Bentonite-Sand Buffer (BSB) –50% bentonite and 50% sand by mass; (iii) Dense Backfill (DBF) –70% crushed granite, 25% lake clay and 5% bentonite by mass; (iv) Light Backfill (LBF) –50% bentonite and 50% crushed granite by mass; and (v) Gapfill (GF) –100% bentonite clay likely fabricated in the form of dense pellets.

In addition to the above noted testing programs, the NWMO has also contributed to the **Ba**ckfill and **Clo**sure (BACLO) project. This work was conducted as part of a multi-party (SKB, Posiva, NWMO) study on piping, erosion and backfill stability done in several laboratories and at the Äspö laboratory in Sweden. Recently, the manner in which water will be taken up by or transported through an assembly of densely compacted clay blocks and bentonite pellets, configured to represent the tunnel fill in an emplacement room, was assessed. A schematic of the laboratory testing apparatus is illustrated in Figure 3.3. Results show that the erosion rate was affected by the inflow rates and the initial condition of the tests, but the erosion rate was not excessive in any of these tests. Additional BACLO testing involved laboratory tests to examine the mechanical (strain) interactions between two dissimilar components of the clay-based sealing system.

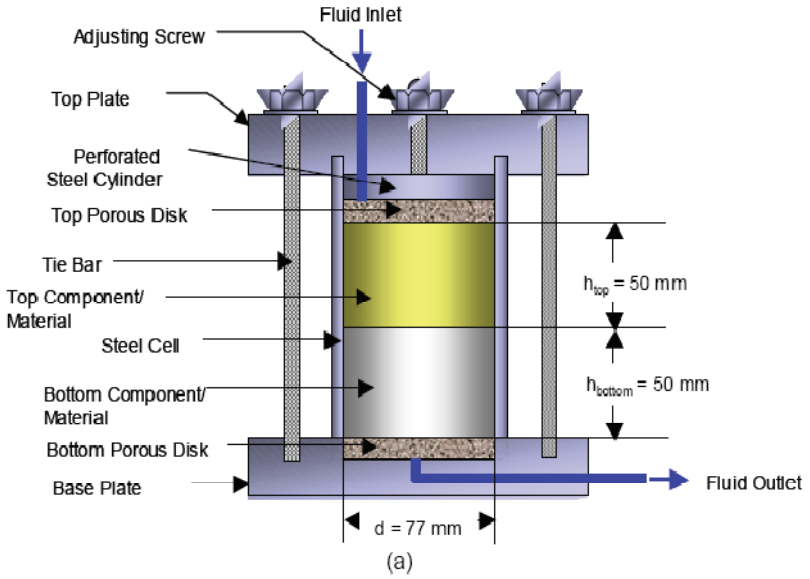


Figure 3.3: Illustration of laboratory-scale sealing material tests

3.3.1 Consolidation and Triaxial Testing Program

Groundwaters at proposed repository depths can contain significant quantities of dissolved salts and an increase in salinity is known to decrease the swelling potential and increase the hydraulic conductivity (Dixon 2000) of barrier materials containing a swelling clay mineral component. Salinities, in terms of Total Dissolved Solids (TDS) at proposed repository depths, can vary from 8 to >100 g/L in the Canadian Shield crystalline rock to greater than 200 g/L in Ordovician-age sediments. Salt speciation is often Na-Ca-Cl at shallow depth trending to Ca-Na-Cl at greater depth according to Gascoyne et al. (1987) and Mazurek (2004).

Baumgartner et al. (2008) completed one dimensional (1D)-consolidation tests using $CaCl_2$ solutions at salinities up to 100 g/L in the initial stages of developing the behavioural database for sealing materials. Baumgartner et al. (2008) observed that specimen preparation affected the behaviour of the clay-based sealing materials. As a result, one of the design decisions for preparing the sealing materials is whether fresh or saline water should be used in sealing

material preparation. Priyanto et al. (2008a and 2008b) investigated the effect of salinities up to 250 g/L on the behaviour of HCB, DBF and LBF using 1D-consolidation tests. Priyanto et al. (2008a) focused on the effect of $CaCl_2$ saline solutions (up to concentrations of 250 g/L) on the properties of bentonite based materials. Priyanto et al. (2008b) investigated the effect of NaCl solution with concentration up 250 g/L on the 1D-consolidation behaviour of clay-based sealing materials and compared the results with Baumgartner et al. (2008) and Priyanto et al. (2008a) to examine the effect of different type of salt solutions (NaCl versus $CaCl_2$) on the behaviour of clay-based sealing materials. In a limited number of tests, Priyanto et al. (2008b) found that similar specimens with 250 g/L NaCl have a higher hydraulic conductivity than specimens using 250 g/L $CaCl_2$ and for a similar salt concentration of 250 g/L, the NaCl solution reduces swelling pressure of the HCB specimen more than the $CaCl_2$ solution.

The first phase of triaxial testing investigated the behaviour of LBF and DBF saturated with distilled deaired water (Blatz et al. 2008). The results of the triaxial testing program provided the isotropic consolidation and stress-strain properties of light backfill (LBF) and dense backfill (DBF) materials under saturated conditions. These properties are required parameters for simulating the behaviour of these materials during numerical modeling. The tests were conducted under both drained and undrained conditions. The results allow interpretation of both strength and deformation or stiffness parameters (i.e., Bulk Modulus and Young's modulus) providing materials parameters for use in numerical models. The results of the testing program indicated that the Bulk Modulus for the LBF was 2.8 MPa and the average Young's Modulus for the material was 155.9 MPa. The strength of this material was similar to that of natural glacial lake clays. The DBF material was found to be both stiffer and stronger than the LBF. The Bulk Modulus for the DBF is 10.7 MPa and the average Young's Modulus for the material is 261.7 MPa. The next phase was to consider the environmental effects on the performance of barrier materials, including the effect of high salinity pore water. The preliminary results on a limited number of tests show a higher peak strength when LBF is compacted and saturated with saline pore fluid.

3.3.2 Microbial Studies in Repository Sealing Systems

One of the key performance requirements of the repository sealing system is to suppress microbial activity at or near the used fuel container surface in a deep geological repository. The microbial activity may cause microbiologically influenced corrosion (MIC) and this may affect the service life of used fuel containers in a repository.

Samples of Ordovician sediments (Queenston shale and Cobourg limestone) were obtained from Ontario Power Generation Inc. for preliminary microbial characterization in support of the NWMO's technical R&D program (Stroes-Gascoyne and Hamon, 2008a). Results suggested that in accordance with expectations, based on measured water content (0%) and very low water activity (<0.2), no viable (halophilic or other) bacteria were present in the limestone rock but that some contamination of the limestone sample with common (facultative) aerobic cells occurred, likely during drilling or sample handling. The results for the shale sample indicated the presence of viable microorganisms. Because of the presence of certain markers, it cannot be ruled out that some of the microorganisms could be indigenous to the shale and survived for a long time in situ as spores in the shale formation. However, this is expected to be very unlikely because of the high similarity with common aerobic surface bacteria.

An important role of highly compacted bentonite is the reduction of significant microbial activity near the used fuel containers in a deep geological repository, which would reduce or eliminate

the possibility of MIC. In a highly compacted bentonite buffer, previous work determined that a dry density of ≥1.6 g/cm^3 or a porewater salinity of > 100 g NaCl/L would keep microbial culturability at or below background levels (i.e., ≤ 2 x 10^2 Colony-Forming Units/g) (Stroes-Gascoyne et al. 2006, 2007). In order to fill in some of the gaps left by the previous study, Stroes-Gascoyne and Hamon (2008b) examined the effects of intermediate NaCl porewater concentrations (i.e., 60, 70, 80 and 90 g/L) on the culturability of microbes in compacted bentonite at target dry densities of 1.2, 1.4, 1.6 and 1.8 g/cm^3 . In addition, the effects of a porewater salinity of 0 and 100 g NaCl/L on microbes in compacted bentonite at intermediate dry densities (i.e., target dry densities of 1.1, 1.2, 1.4 and 1.5 g/cm^3) were also examined. The additional data suggest that the previous requirements for bentonite dry density or porewater salinity to keep microbial culturability at or below background levels in the highly compacted bentonite buffer (i.e., ≥ 1.6 g/cm^3 or > 100 g NaCl/L) have been confirmed and that those requirements could likely be lowered to ≥ 1.4 g/cm^3 or > 50 g NaCl/L (see Figure 3.4). Stroes-Gascoyne and Hamon (2008b) also recommended that actual pore sizes be measured in the bentonite to further assess microbially influenced corrosion and that a variety of bentonite types be assessed.

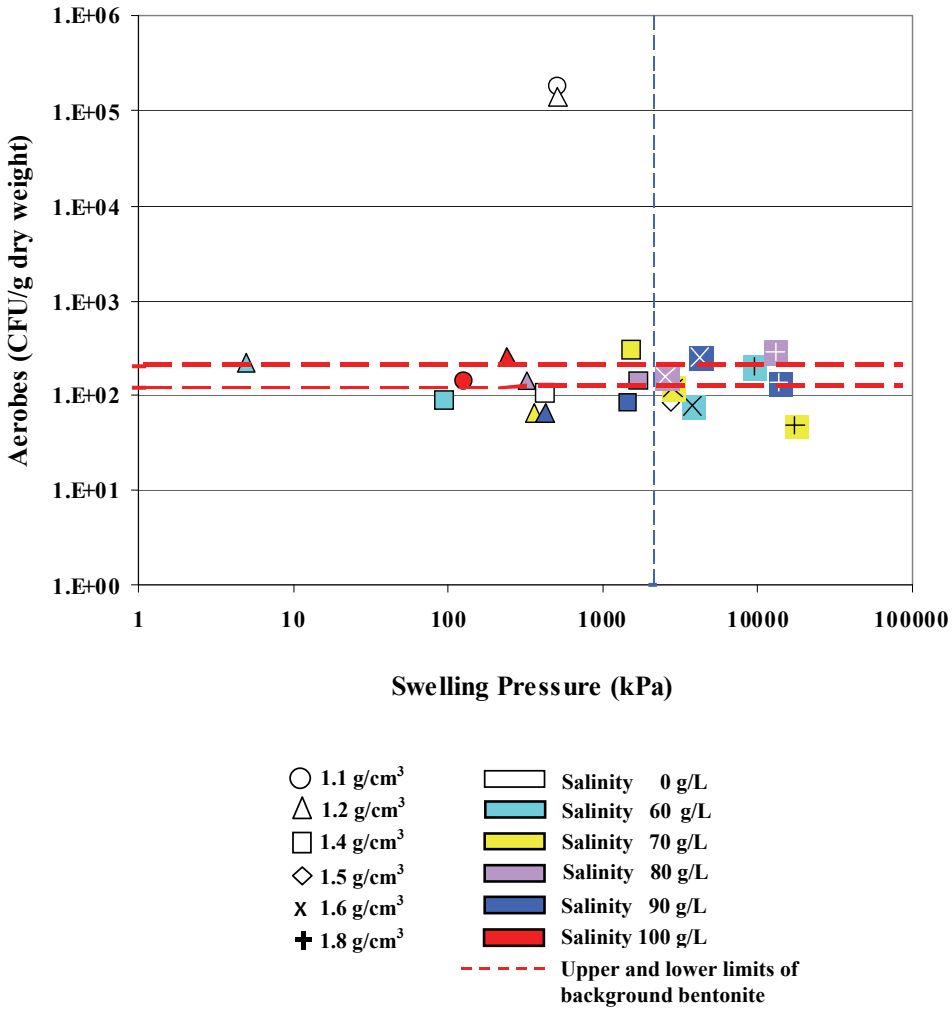


Figure 3.4: Aerobic culturability in compacted bentonite as a function of swelling pressure (new data)

3.4 REPOSITORY DESIGN

In 2008, the NWMO continued to develop concepts for a deep geological repository in both sedimentary and crystalline rock. The design of the repository will take into account a wide variety of design considerations, including; the used fuel packaging, the geological environment and location. In order to complement Canadian knowledge of developing a DGR in crystalline rock, Read (2008a) compiled rock engineering information for the potential use of sedimentary rock as a host medium. In addition, Read (2008b) assessed whether the presence of a repository could induce large-scale fractures to form in typical rock formations encountered within Canada.

In support of the future development of a used fuel DGR, Kuzyk and Martino (2008) documented the managerial experiences and lessons learned in achieving the high quality excavations that were necessary for the construction of the AECL Underground Research Laboratory (URL). This laboratory was constructed in the 1980s in the Lac du Bonnet batholith in southeastern Manitoba. A sound geotechnical understanding of in situ conditions was required in support of the large-scale experiments that would be conducted in the granitic rock mass.

To achieve the necessary knowledge of the URL's geological conditions, it was required that the quality of the excavation meet a specific requirement, and that the geological mapping and geotechnical assessment by AECL staff be incorporated in the excavation cycle. The quality of the excavation is shown in the photograph in Figure 3.5.

Figure 3.5: Controlled drilling and blasting used to provide smooth rock surface for geological mapping during excavation of AECL's URL

Achieving this excavation quality and incorporating the geological mapping and geotechnical assessment activities into the excavation contract, particularly during shaft excavation, was very challenging. This required a form of contract that both supported the needed characterization activities and recognized the contractor's objectives. The onus is on the owner of a facility to identify an appropriate contract format in consultation with potential contractors that shares the risks fairly, allows the owner's excavation quality and assessment goals to be achieved, and allows the contractor to complete the work scope with a reasonable return. It is also necessary to closely monitor the progress of the work to ensure the specified requirements are met.

The preferred form of contract developed at the URL for shaft sinking was a cost plus fixed fee contract format, which facilitated quality excavation in a manner that encouraged cooperation between the owner and the contractor. Integration of the contractors' organization into the shaft extension project management facilitated close cooperation and was the key for success in these contracts.

3.4.1 Application of Rock Engineering in Development of a Deep Geological Repository

Since the 1980's, considerable research has been completed on the potential for crystalline rock of the Canadian Shield as a host medium for a used fuel DGR, but less has been compiled for the potential use of Canadian sedimentary rock. Therefore, the NWMO has expanded its technical R&D program to include further analysis of sedimentary rock as a potential host medium. Read (2008a) identified key rock engineering aspects to be considered in advancing the understanding of sedimentary rock for a DGR.

Read (2008b) also examined four DGR designs in three possible host rocks, including crystalline and sedimentary rock types and concluded that large-scale fracturing in the far-field is implausible given the expected in situ stress conditions in relation to rock strength. Near-field damage development and fracturing are expected in many of the DGR scenarios in the different rock types, but these near-field effects are not expected to lead to large-scale fracturing that would compromise the integrity of the DGR and surrounding rock mass. Read (2008b) identified thermo-poroelastic effects as one possible driving mechanism that should be studied further, and provided other recommended analysis and characterization activities to further validate his conclusions.

3.4.2 Numerical Modelling of a Deep Geological Repository

It is important to define suitable properties for the repository sealing systems as well as the rock mass in support of repository design and design optimization. Therefore it is necessary to develop both accurate numerical models that can be used to assess the performance of the repository under realistic operating conditions and the properties of the host rock and the sealing system materials that are needed to apply the models. In 2008 the NWMO conducted a preliminary assessment of both commercial and academic numerical codes available for modeling a used fuel DGR. In addition, the NWMO assessed laboratory equipment available for determining thermal properties of rock for future laboratory investigations.

In 2008, several numerical models of the used fuel DGR were carried out including: compliance models of both the in-floor borehole method and the horizontal borehole method; and a thermal sensitivity analysis of the NAGRA-type horizontal used-fuel container placement method. Chandler (2008) carried out a compliance model on the in-floor borehole method and on the

horizontal borehole method using Fast Lagrangian Analysis of Continua (FLAC) analysis software code. Compliance modelling can provide insight into density changes of swelling clay materials upon saturation. In both the in-floor and horizontal borehole options, highly compacted bentonite (HCB) was placed adjacent to a material comprised of bentonite pellets or granules, and upon saturation, the expansion of the HCB resulted in a reduction of its dry density concurrent with a compression of the adjacent bentonite pellet materials. The numerical models indicated that minimum dry density of the bentonite adjacent to the used-fuel container would result in microbe culturability to be at or below background levels.

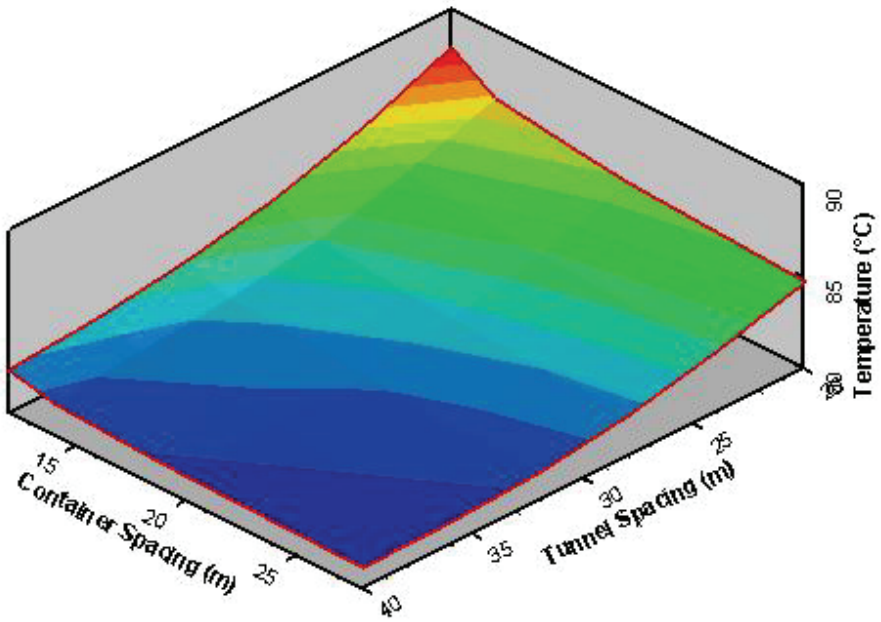


Figure 3.6: Maximum container-surface temperatures as a function of various repository spacings

Guo (2008) presented the first part of a series of the modelling for a deep geological repository using the horizontal tunnel placement method for a used-fuel container in sedimentary rock. This study included a series of thermal sensitivity analyses to investigate the influence of tunnel spacing and container spacing on the development of the container-surface temperature and the tunnel-surface temperature in a repository and an example of the maximum container surface temperatures given a specific thermal conductivity for a buffer material is shown in Figure 3.6.

Guo found that the spacing of the placement rooms and the used fuel containers would be sensitive to the thermal conductivity of the clay-based engineered barrier systems and the key parameter for engineering design is the thermal conductivity of the buffer material surrounding the container.

4. GEOSCIENCE

4.1 INTRODUCTION

The Geoscience work program is designed to develop a geoscientific basis for understanding long-term geosphere barrier performance, as well as building confidence in deep geological repository safety in both sedimentary and crystalline settings. This is achieved through a multidisciplinary approach involving the coordinated effort of research groups drawn from Canadian universities, consultants, federal organizations and international research institutions.

The main objectives of the NWMO's geoscience R&D program are to:

- Develop tools and methods to improve NWMO's geosphere characterization capabilities and to develop readiness for evaluating potential candidate sites in potentially willing host communities;
- Advance the understanding of long-term physical and geochemical evolution of the geosphere at time scales relevant to repository safety; and
- Improve numerical methods to assess the geosphere evolution and its response to long-term perturbations, and explore the influence of uncertainties arising from limitation of site characterization.

The following sections outline the activities of the geoscience work program in 2008. The activities are organized into sections entitled developments of site evaluation tools and methods, long term geosphere stability, numerical tools and methodologies and international projects.

4.2 DEVELOPMENTS OF SITE EVALUATION TOOLS AND METHODS

NWMO's evaluation of potential candidate sites for a deep geological repository will be conducted over many years in a stepwise approach starting with initial screening studies and site feasibility studies based on available geoscientific information, followed by detailed site characterization involving field investigation activities once potential candidate sites have been identified. In 2008, NWMO initiated a number of activities aimed at developing readiness for evaluating potential candidate sites in willing and informed host communities, focussing on the tools and methods that would be used during the early stages of the site evaluation process. Activities include the development of preliminary geoscientific site evaluation criteria, the collection of geoscientific background information on the four nuclear provinces, a state-of-the-science review of airborne and geophysical non-intrusive site investigation methods, the development of Seismic Hazard Assessment guidelines and the development of a GIS system to manage and analyze geospatial data that will be collected during the siting process. Research and development work continued in number of other core areas relevant to site characterization such as the development of laboratory techniques for matrix porewater extraction and characterization and the evaluation of transport properties of both crystalline and sedimentary rock.

In parallel, a great deal of practical site characterization experience is being gained by NWMO staff through their involvement in site characterization activities at the Ontario Power Generation

planned Low and Intermediate Level Waste Deep Geologic Repository at the Bruce site in Ontario.

4.2.1 Geoscientific Site Evaluation Criteria

As part of the design of a collaborative siting process, the NWMO initiated the development of preliminary geoscientific criteria that will be used to evaluate the suitability of potential candidate sites in willing and informed host communities. Activities in 2008 included the review of regulatory requirements, technical siting factors identified in NWMO's siting study report (NWMO 2005) and international guidance and experience. Preliminary geoscientific criteria being developed to support development of the siting process are considering the following general questions:

a) Are the characteristics of the host rock appropriate to ensuring the long-term containment and isolation of used nuclear fuel from humans, the environment and surface disturbances?
b) Is the rock formation at the site geologically stable and likely to remain stable over the long-term such that the integrity of the repository will not be compromised by natural events such as earthquakes and climate change?
c) Are conditions at the site suitable for the safe construction, operation and closure of the repository?
d) Is human intrusion at the site unlikely, for instance through future exploration or mining?
e) Can the geologic conditions at the site be easily characterized and described on dimensions that are important for demonstrating long-term safety?

The NWMO is planning to issue the preliminary geoscientific criteria as part of the NWMO's draft siting process proposal for public review in 2009.

4.2.2 Background Geoscientific Information on the Four Nuclear Provinces

NWMO is collaboratively developing a siting process with Canadians to seek an informed and willing community to host a used nuclear fuel deep geological repository. For fairness, the site-selection process will be focussed within the four nuclear provinces that are involved in the nuclear fuel cycle (Saskatchewan, Ontario, Québec and New Brunswick). In order to develop a better understanding of the geoscientific characteristics of each nuclear province and prepare for initial stages of the siting process, the NWMO is in the process of collecting background geoscientific information on each nuclear province.

In 2008, NWMO initiated a review of available published geoscientific information to produce a geoscientific compilation report for each nuclear province. Important background publications include previous NWMO reports such as Mazurek (2004) and Percival and Easton (2007). The key topics compiled for each nuclear province include: i) geological regions, ii) lithostratigraphy, iii) structural geology, iv) geological stress and seismicity, v) quaternary geology vi) regional hydrogeology, vii) regional hydrogeochemistry and viii) economic resources. Available sources of geoscientific information such as geological maps, borehole and geoscientific databases and general literature reference lists were also compiled. The final geoscientific compilation reports are expected to be available in 2009.

4.2.3 Review of Surface Based Site Characterization Methods

Airborne and surface-based, non-intrusive geophysical methods may be used to assess rapidly and cost-effectively numerous geoscientific characteristics of interest to a range of disciplines (including the geological, hydrogeological, hydrochemical, geotechnical, transport and biosphere properties models) which together form a geosphere characterisation program.

The objective of this work program was to develop a state-of-the-science review report on available satellite, airborne and surface-based, non-intrusive geophysical site characterization tools and methods that could be used during the initial stages of the siting process. By also summarizing recent technological advances in this area, the review report would allow the NWMO to make informed decisions when selecting the tools and methods for conducting initial site evaluations.

This review, completed by Emsley et al. (2008), addressed a number of aspects including the geoscientific characteristics that could be assessed by various methods, their accuracy, limitations and constraints, applicability to sedimentary and crystalline formations, commercial availability in Canada, survey time scales, strengths and weaknesses of each method, etc. The study also included a review of key elements to be considered during survey design and also the geophysical methods and techniques that have been used in similar site characterisation programs in other countries.

Geophysical methods and remote sensing have been an integral part of the geosphere characterisation in all repository studies in both crystalline and sedimentary rock. Many satellite, surface and airborne techniques have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development and the available technology at the time.

The review of borehole-based geophysical techniques that could be used in later stages of the siting process will be addressed in a future work program.

4.2.4 Seismicity

Seismicity is one of the siting criteria or evaluation factors that will be considered during the siting process. The seismic design of a deep geological repository is in essence similar to that of underground structures such as deep tunnels and mine openings with the exception of the much longer earthquake return periods that need to be considered. Seismic response of underground structures is distinct from the response of most surface structures because of their complete enclosure in the host rock. Field observations have shown that underground structures suffer appreciably less damage than surface structures and deep tunnels are safer and less vulnerable to earthquakes than shallow tunnels (Power et al. 1998). The seismic design of a DGR requires an understanding of the anticipated ground shaking at repository depth as well as an evaluation of the response of the host rock and repository components to such ground motion.

The design approach consists of three main steps:

a) Seismic Hazard Assessment for the prediction of the seismic risk and environment at the site;
b) Evaluation of the ground response to ground shaking at depths;
c) Assessment of the structural response of the repository components to ground shaking.

The first step involves the prediction and selection of the seismic parameters that will be used for the seismic analysis. The main parameters of interest include the size of the earthquake as well as the frequency content and duration of the ground motion. The second and third steps involve the host rock response in terms of ground shaking and fault reactivation, and the structural response of the various engineered components of a DGR (e.g. rock support systems, waste containers, sealing materials etc.). These are mostly site specific engineering issues that can be addressed through established tools and methods used for the design of underground structures.

In 2008, Geoscience seismicity R&D activities focused on developing a methodology for Seismic Hazard Assessment in low seismicity areas, which is a challenging task because of the long timeframes that are considered for deep geological repositories (>100, 000 years). Other R&D activities include understanding attenuation of seismic ground motion with depth and supporting the Canadian Hazards Information Service maintained by Geological Survey of Canada. R&D work on seismicity will be expanded as the siting process progresses and potential hosting areas are identified.

4.2.4.1 Seismic Hazard Assessment Methods

Canada experiences an average of 3,500 earthquakes each year. Of these earthquakes, approximately half occur in western Canada, with the remainder mostly in the east. Western Canada, particularly the province of British Columbia, is considered to be the most seismically active area in the country. There is also moderate seismic activity observed in the Arctic regions, the St. Lawrence River and along the east coast of Canada. In contrast, the regions of central and most of eastern Canada are located in low seismic regions of the North America Plate which include the stable Cratonic Regions. The seismic stability of these regions makes them attractive for siting of long-term nuclear waste management facilities. However, because of the short history of seismicity data records, particularly for rare large magnitude events, it can be challenging to define reliable seismic source zones and conduct seismic hazard assessment for critical facilities requiring the consideration of large return periods such as deep geologic repositories. Current Seismic Hazard Assessment method for low seismicity areas relies on analogous data from similar regions around the world to augment incomplete geological data and lack of seismicity record. However, the predictions derived using this approach may not be fully reliable as they are based on blending data from regions that may not have comparable geological and technical settings (Fenton and Adams, 1997; Fenton et al., 2006; Atkinson and Martens, 2007).

In order to address the above uncertainties, NWMO initiated, in collaboration with Dr. Leonardo Seeber and Dr. Klaus Jacob of Lamont -Doherty Earth Observatory, Columbia University, a work program which includes the conduct of a state-of-the-science review of existing seismic hazard assessment approaches and the development of new guidelines for conducting seismic hazard assessment studies in low seismicity regions.

A state-of-the-science review on the applicability of paleoseismology methods to geological settings that are typical of the four nuclear provinces was also initiated to assess whether traditional Seismic hazard Assessment methods could be enhanced and complemented by paleoseismology studies.

4.2.4.2 Seismic Monitoring of the Canadian Shield (Canadian Hazards Information Service)

The Canadian Hazards Information Service (CHIS) of the Geological Survey of Canada (GSC) continued to conduct monitoring of the low seismicity region in the northern Ontario and eastern Manitoba portions of the Canadian Shield. CHIS' network consists of twenty-six seismograph stations. During this period 68 seismic events were recorded ranging from magnitudes (m_N) of 1.1 to 3.0 (Figure 4.1). The largest few events occurred in the James Bay and the Cochrane-Kapuskasing regions of Ontario with magnitudes ranging between 2.8 and 3.0. The magnitude-recurrence curves for the events recorded in 2007 and for the events cumulated from 1987 to 2006 are shown on Figure 4.2.

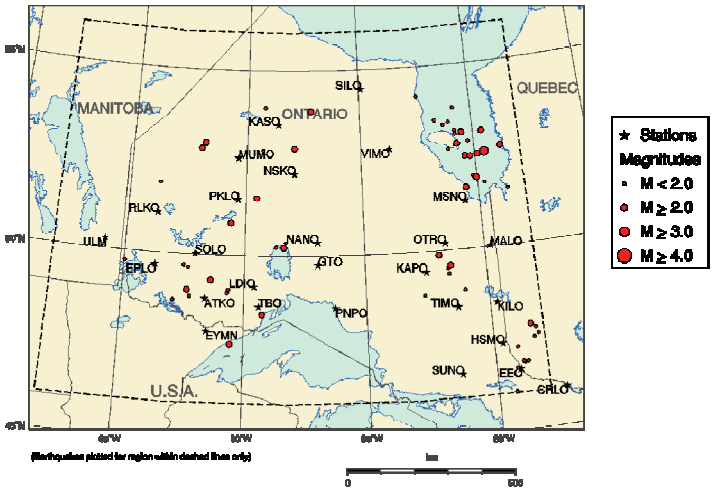


Figure 4.1: 2006 Seismic events in Northern Ontario and adjacent areas

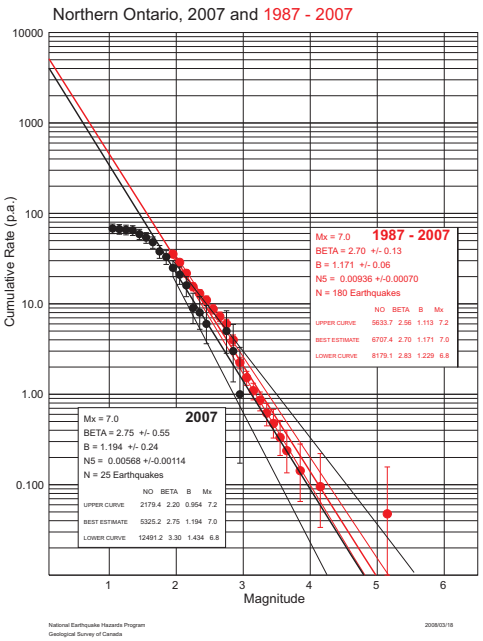


Figure 4.2: Recurrence curves for Northern Ontario

The NWMO is planning to initiate a study in 2009 to investigate the use of various waveform modelling methods to improve the accuracy of focal depth determination for shallow earthquakes. Focal depth is an essential component for assessing the seismic hazard and the fault-rupture risk at a repository site. Accurately determined focal depths could provide useful information on the thickness of seismogenic layers.

4.2.4.3 Seismic Response of Underground Facility- Sudbury Neutrino Observatory (SNO)

Monitoring continued for a second year (2008) within the PUPS (POLARIS Underground Project at Sudbury Neutrino Observatory) project. The main objective of PUPS is to investigate of the host rock response at repository depths under seismic ground motions. It is known from case histories that ground motion at depth is less severe than that measured at the surface (EPRI 1994) and that underground structures are less susceptible to damage during an earthquake (Power et al. 1998). This experiment will help in quantifying the amount of seismic ground motion reduction at various depths also known as surface effect.

In 2008, signals from 60 local seismic events recorded from PUPS and the nearby POLARIS station SUNO (at Sudbury) were analyzed (Figure 4.3). Based on almost two years of observations of local induced and mining seismicity (m_N=1.5-3.0), average spectral ratios of the ground motion at the surface to that at depth were calculated to characterize the response at frequencies 0.5-30 Hz. Overall, both response spectra and Fourier acceleration spectra indicate that underground vertical and horizontal ground motions are lower than those at the surface at frequencies from 0.8-2.5 Hz. The difference has a peak amplitude of about 0.5 log units (factor of 3), in a narrow frequency band from about 1.6-2.0 Hz. At higher frequencies, vertical components observed at the surface have similar amplitudes in comparison with those underground, while horizontal components at the surface are slightly amplified relative to those at depth.

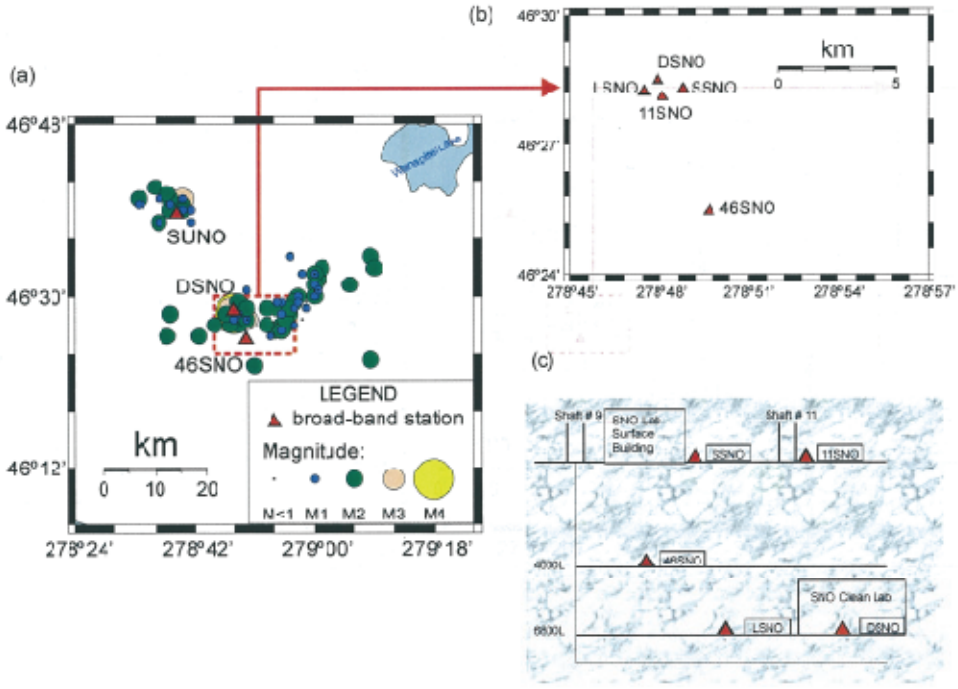


Figure 4.3: (a) Station and epicentre locations; (b) Station configuration; (c) Cross-section of Sudbury Neutrino Observatory lab location

The findings are generally consistent with theoretical concepts of near-surface response showing that this peak is related to the presence of strong surface waves that amplify motions for the surface sites under some conditions. These surface waves are strongly attenuated at

depths of >1 km, leading to reduced amplitudes underground. The results also indicate that the surface waves and the corresponding frequency range are dependent on the characteristics of the source, such as the depth and distance to the site. Further monitoring and analysis is planned for 2009 to better describe the full range of surface wave effects and their potential attenuation at underground sites.

4.2.5 Matrix Pore Water Characterization

The compositions of groundwaters in deep rock formations are required for near-field performance and safety assessment calculations, and for models involving groundwater transport or evolution. There is little information on the composition of these saline waters; most has come from brines collected from oil and gas producing wells. The compositions of water within the rock matrix (matrix pore waters) of crystalline and sedimentary formations may have compositions similar to those of the groundwaters. However, direct information on pore water composition is required in order to support this hypothesis.

Beginning in 2005, a collaborative work program was undertaken, in collaboration with Gascoyne GeoProjects and the U.S. Geological Survey, to develop a protocol for determining the elemental and isotopic compositions of pore waters in deep crystalline environments from core samples. Several methods to determine pore fluid composition from freshly drilled core were investigated and compared, including crushing and leaching of the core, measuring the composition of water diffusing out of the core ('out-diffusion'), displacing fluids from the core using high speed ultracentrifuge methods, and collecting seepage waters from underground boreholes. Of the methods investigated, the ultracentrifugation technique showed particular potential, because it can be used to rapidly and directly extract pore waters for determination of chemical and isotopic compositions (Gascoyne et al., 2009). In the ultracentrifugation technique, pore water is extracted by spinning broken core at a rate of 15,000 rpm under controlled conditions of temperature and pressure. A one year research program was initiated in 2007 to investigate the feasibility of the ultracentrifugation method for application to sedimentary rock (Gascoyne and Hobbs, 2009). This research included a review of the ultracentrifugation technique as previously applied to different rock types and the application of the method to freshly-drilled limestone core from the Bowmanville Quarry in Ontario. Results from this study demonstrated that it was possible to extract small quantities (<0.5 ml) of pore water from the low porosity limestone samples (Gascoyne and Hobbs, 2009). However, the chemical compositions and salinity of the extracted pore water were found to vary with subsequent extractions on the same core.

In 2008, a two-year work program began to further investigate and test the ultra high speed centrifugation technique for the determination of matrix pore water compositions in sedimentary rocks. The first objective of this work program is to determine if the variations observed previously (variations in measured moisture contents, as well as variations in pore water compositions with different extraction times) reflect natural variability in the samples and not the result of changes induced by sample handling or experimental procedures. Preliminary results show good reproducibility between replicate analyses of moderate porosity sedimentary rocks (Figure 4.4), however as of yet, no water was able to be extracted from the lower porosity samples.

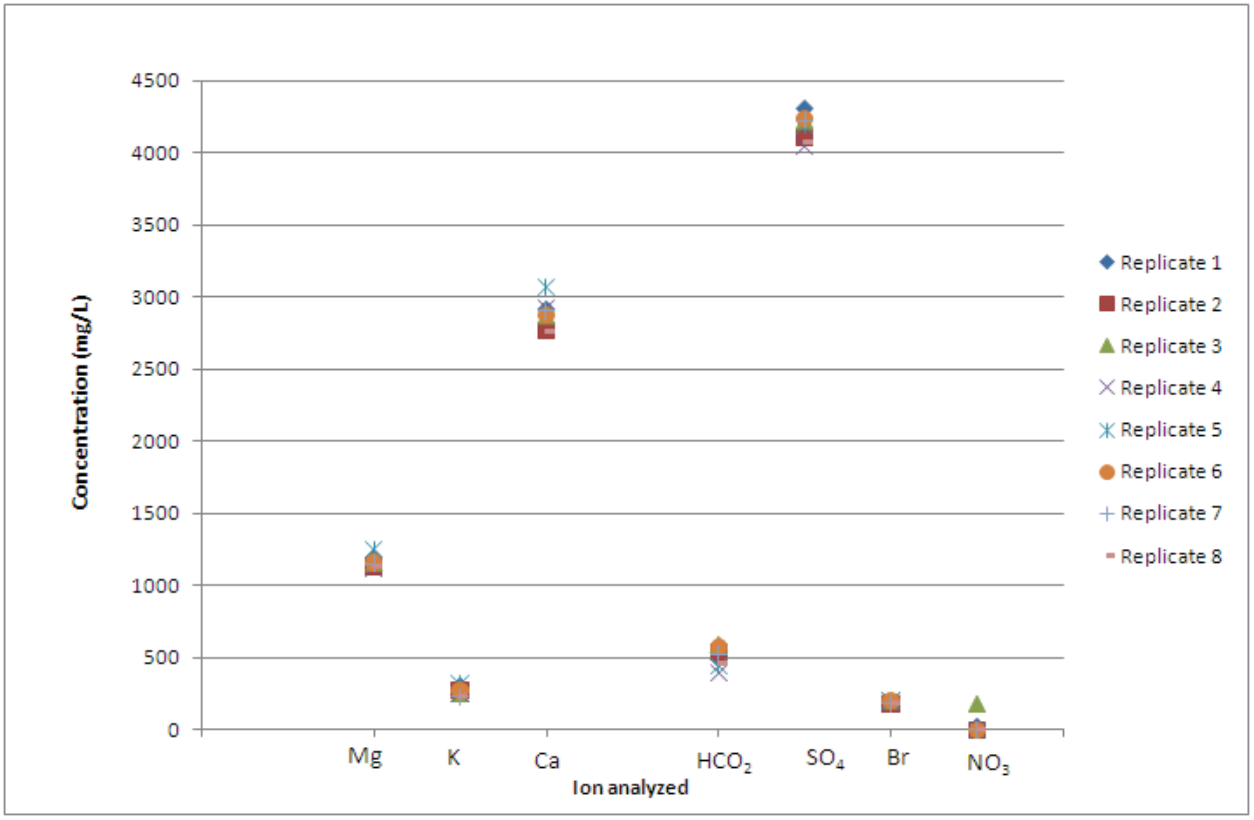


Figure 4.4: Preliminary data from the ultracentrifugation work program illustrating reproducibility of results for replicate analyses of sample 314.89

4.2.6 Radionuclide Transport Processes

4.2.6.1 Diffusion in Sedimentary Rock

Diffusion is expected to be the dominant solute transport mechanism within low permeability geological formations. Understanding the diffusive transport properties of sedimentary and crystalline rocks is of particular importance in assessing the ability of the geosphere to contain and isolate radioactive wastes at timeframes of 100,000 years and beyond. Predictions of mass transport by diffusion require information on the rock properties including porosity, pore geometry, pore interconnectivity, effective diffusion coefficients and permeability. Standard investigation techniques such as through-diffusion measurements, which are used to estimate bulk values of porosity, rock capacity factor, and an effective diffusion coefficient, provide a single bulk measurement for these parameters in each sample. The development and testing of experimental protocols to characterize the bulk diffusive and mass-transport properties of rock matrices using standard through-diffusion measurements were described by Vilks and Miller (2007).

To study diffusive transport and evolving reactivity in sedimentary rock (sandstone, limestone and shale), an X-ray radiography technique for characterizing and quantifying the concentration

distribution of an iodide tracer solution in rock samples is being developed and tested by the University of New Brunswick as part of an NSERC Strategic Project Grant (Figure 4.5). This method has the potential to resolve the spatial distribution of porosity and diffusion at a smaller scale than thought possible using through-diffusion techniques. This method also allows for visualization of tracer during diffusion, which can be used to detect preferential diffusion pathways and to assess the influence of sample heterogeneity. Radiography also allows estimates of the diffusion coefficient within a sample before steady-state is reached, because time-dependent diffusion profiles are measured. This may result in substantially shorter measurement times in comparison to through-diffusion techniques.

In 2008, a comparison of the through-diffusion and 1-D X-ray radiography technique was completed, in which paired samples of archived core of the Queenston shale from the Niagara region in Ontario and Cobourg limestone from the Darlington area in Ontario were examined using both techniques (Cavé et al., 2009). Similar values for the effective diffusion coefficient (De) were determined using the radiography and through-diffusion methods. Work continues in 2009 to further develop the x-ray radiography technique, and to examine variations in the diffusive properties across a sedimentary rock sequence underlying southwestern Ontario.

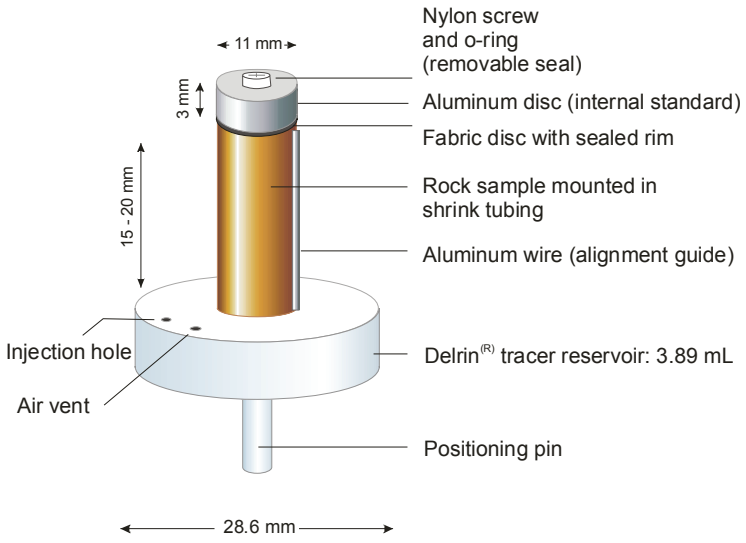


Figure 4.5: Diagram of the diffusion cell used for diffusion experiments by X-ray radiography

4.2.6.2 Scale-Dependency of Diffusion

Characterization of the diffusive properties of low permeability rocks is an important component of the safety case for a deep geological repository, because diffusion is expected to be the dominant solute transport mechanism in this environment. Laboratory determination of diffusive properties is often at a small (cm) scale, and an understanding of the scale-dependency of diffusion is required in order to evaluate the applicability of laboratory-derived diffusion coefficients to scales relevant to a deep geological repository.

Work continued in 2008 to develop and advance a structured understanding of diffusive processes as they affect the retention and retardation of contaminants migrating through fractured crystalline plutonic and sedimentary rock settings typical of those encountered in Ontario. A particular focus will be placed on the application of laboratory and in-situ derived effective diffusion coefficients (De) for undertaking sub-surface mass transport predictions. A primary goal is to demonstrate limitations in, and range of, De applicability, taking into consideration rock matrix and pore geometry, stress, infilling mineralogy, rock-water interactions, anisotropy, and scale dependence.

4.2.6.3 Sorption in Saline Waters

Sorption plays an important role in regulating the migration of radionuclides in the geosphere. A Canadian sorption database for the postclosure assessment of a hypothetical repository in the Canadian Shield with groundwater compositions having up to 11 g/L TDS was finalized in 1996. However, NWMO is now also considering sedimentary rock formations. Sedimentary rocks in Canada, for example in the Michigan basin, have been observed to contain brine solutions with Na-Ca-Cl and Ca-Na-Cl brines with TDS concentrations reaching 300 g/L. Therefore, there is a need to establish an understanding of how brine solutions affect sorption on sedimentary rocks, as well as on crystalline rocks since deep groundwaters in the Canadian Shield may also contain brines with TDS values up to 400 g/L.

A state-of-the-science review was initiated in 2008 to review available knowledge with respect to understanding and quantifying the sorption properties of rocks in saline waters (Vilks, 2009). This included an examination of sorption within the Canadian and international nuclear waste management programs in crystalline and sedimentary rock environments and engineering barrier systems, scientific literature on sorption in saline waters, as well as theoretical considerations of sorption processes under saline conditions. While sorption properties of rocks are fairly well understood, the state-of-science review revealed a gap in sorption data for highly saline conditions such as those found at depth in Canadian sedimentary basins. The report made recommendations on the development and testing of experimental protocols, and proposed a path forward for an experimental program to quantify sorption in saline waters within the Canadian used fuel program which will begin early in 2009.

4.2.7 Geographic Information Systems

The site evaluation process will require that a large volume of digital spatial data be managed in an efficient and traceable manner. It is recognized that this is best achieved through the use of Geospatial Information Technology (GeoIT). As the siting process progresses, the NWMO's needs in GeoIT will gradually evolve.

In 2007, the main focus was in acquiring readily-available, open source, spatial data from across Canada with a particular emphasis on the four nuclear provinces. Over 300 individual geospatial layers were gathered, inventoried and categorized into several themes including geopolitical, infrastructure, settlements, geology and environment. For 2008, the goal was to integrate the use of geospatial data within the NWMO to support future decisions and communications. The development and implementation of a Web Mapping Application will provide NWMO staff with the ability to search, explore and view the acquired data inventory layers and to load map-based layers that support their particular needs.

For 2009, work tasks will include augmenting the geospatial data repository, focusing on both technical and social elements representing the four nuclear provinces of Ontario, Québec, New Brunswick and Saskatchewan.

4.2.8 Fracture Network Modelling

Fracture Network Modelling can be useful at all stages of site characterization as it can provide a framework for guiding field investigation activities and developing conceptual geosphere models for groundwater flow and transport modelling, geomechanical analysis and the conduct of uncertainty analysis. In 2008, the NWMO initiated a work program to refine and document a version of the FXSIM3D software application for generating Fracture Network Models (FNMs) to facilitate technology transfer and widen the users' base within the geoscience and geological engineering communities.

FXSIM3D is a research software application developed under Ontario Power Generation's Deep Geologic Repository Technology Program (DGRTP) for creating 3D fracture network models (FNMs) based on a geostatistical procedure that honours a wide variety of different types of data on the location and orientation of sub-surface fractures. The code uses surface expressions of fractures, statistics on fracture density, structural geology principles that govern down-dip behaviour and truncation rules for when lineaments intersect to generate probabilistic FNMs. The FNMs produced by the code consist of equally-likely renditions of fracture geometry, each one being visually realistic and structurally complex, honouring the detail of fracture locations, orientations and other aspects of the fracture geometry, such as the down-dip behaviour of fracture surfaces. The FNM code has been used successfully to simulate fracture networks found at the Whiteshell Research Area (Srivastava, 2002a), as well as for a Canadian Shield site (Srivastava, 2002b). A third FNM based on quarry field data from Lägerdorf, Germany was created in order to validate and verify the fracture network model procedure (Srivastava and Frykman, 2006).

In order to better facilitate the creation of the release version of FXSIM3D, a questionnaire was created and sent to various stakeholders asking for input into which functionalities should be included in the first release version or subsequent versions. Version 1 of FXSIM3D, along with the user manual and verification cases, should be available for release in 2009.

4.3 LONG-TERM GEOSPHERE STABILITY

Long term geosphere stability is concerned with addressing the resilience of key safety functions such as the long term maintenance of favourable containment and isolation characteristics of the geosphere and maintenance of favourable geomechanical and geochemical conditions around the engineered barrier systems. The geological formation must demonstrate resilience to perturbations that may occur within time frames that a relevant to repository safety. Providing evidence and reasoned arguments for the long-term maintenance of favourable hydrogeological, geomechanical and geochemical characteristics throughout past and future perturbations such as climate change events and seismic activity will enhance confidence in the safety case for a deep geological repository.

The long-term stability of the geosphere can be addressed by assessing the signatures of glaciations, which is considered to be the most intense perturbation associated with climate change in northern latitudes. Potential impacts of glacial cycles include: increased stress at repository depth caused by glacial loading; penetration of permafrost to repository depth;

recharge of oxygenated glacial meltwater to repository depth; and the generation of seismic events and faulting induced by glacial rebound following ice-sheet retreat.

Work programs in this area are being directed to improve the understanding of geosphere responses to past and future glaciation cycles and to provide insight into the resilience of the geosphere at repository depths. Geoscience research activities are based on a multidisciplinary approach aimed at collecting multiple lines of evidence drawn from coupled numerical simulations, geochemical studies and paleohydrogeological investigations. The main aspects considered include:

- Expected physical and temporal surface boundary conditions related to future glaciation events by estimating the magnitude and time rate of change of ice sheet thickness, ground surface temperature and permafrost occurrence, amongst other attributes;
- Impacts of glaciation on redox stability using both numerical simulations and paleohydrogeological investigations;
- Evolution of deep groundwater flow systems and impacts of Coupled Thermo-Hydro-Mechanical effects imposed by glacial cycles;
- Seismicity and faulting induced by glacial rebound; and
- Analogue studies to assess the influence of ice-sheet characteristics and permafrost on groundwater flow system evolution using field investigations.

Geoscience work programs related to glaciation impacts on the geosphere have focused primarily on crystalline rock formations. One of the objectives for 2008 was to expand the program to address impacts on sedimentary rock formations. To support the planning of R&D activities in this area, a comprehensive review of the impact of glaciation on sedimentary basins was initiated. Summaries of ongoing work programs are provided in the following sections.

4.3.1 Surface Boundary Conditions during Glacial Cycles

One essential element in assessing the potential impact of glaciation on a DGR is the ability to adequately predict the surface boundary conditions during glaciation cycles such as permafrost extent and depth, ice-sheet extent, thickness and kinematics, ice-sheet hydrology, as well as other attributes. For the purpose of the NWMO's case studies on glaciation, these boundary conditions have been predicted using the University of Toronto's Glacial Systems Model (GSM) in collaboration with Dr. W.R. Peltier (Peltier, 2006). The University of Toronto Glacial Systems Model is a state-of-the-art model of continental scale ice-sheet evolution whose application acknowledges that the detailed space-time history of a particular continental scale glaciation event is not uniquely predictable. Nevertheless, it is possible to characterize the range of possibilities in a probabilistic manner and thereby to understand the extent to which events may differ from one another. The GSM has been enhanced to enable calibration using a Bayesian methodology. This methodology allows the model to reconcile a large body of observational constraints concerning ice-age advances and retreats of ice cover over the North American continent during the Late Quaternary period of Earth history.

Although the goal of this work program is to predict the characteristics of a range of plausible, future glaciation cycles, this would require the availability of an accurate model of coupled climate ice-sheet evolution as well as knowledge of future variations in greenhouse gas concentrations. Since neither of these is presently available, the work program must rely on the

extensive knowledge of past events, such as the most recent Laurentide glaciation, together with the assumption that a future event would most probably be similar in nature.

Recently, the GSM has been applied to explore the time-dependent nature of surface boundary conditions that would be representative of a southern Ontario setting (Peltier, 2008). Because southern Ontario is located near what was the southern edge of the Laurentide ice-sheet during its sequence of Late Quaternary expansions, it is a region of strong temporal variability in glaciation processes. One example of continental scale distribution of ice sheet thicknesses for one of the GSM models near glacial maximum is shown in Figure 4.6.

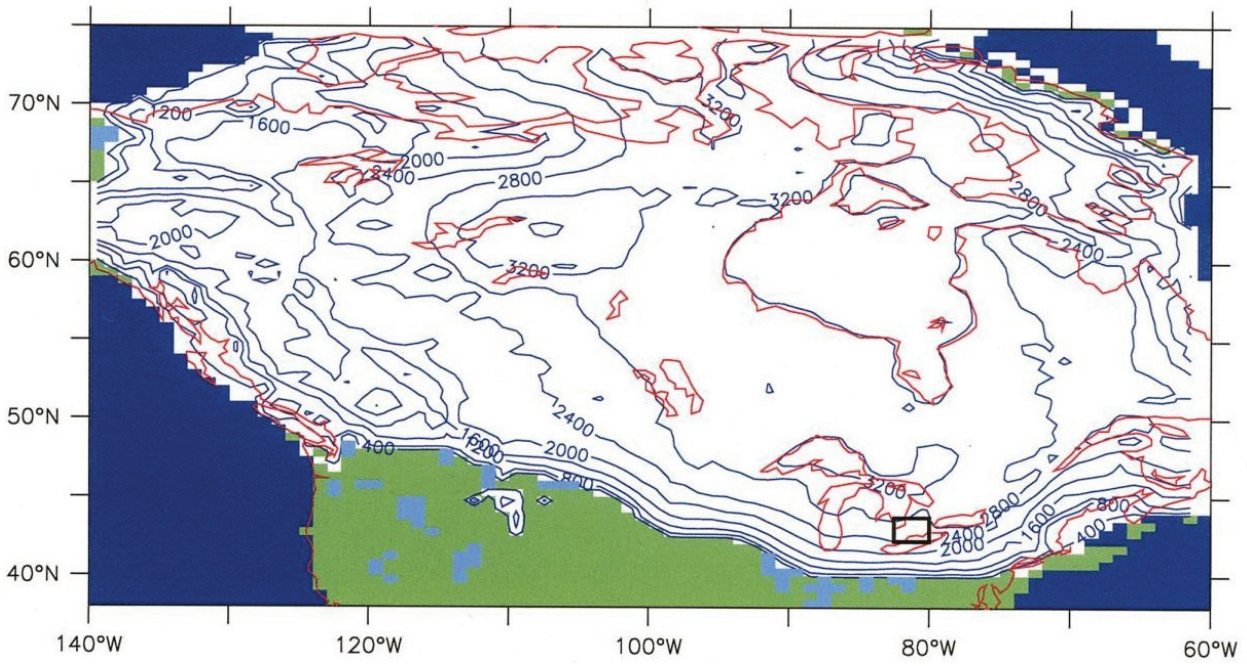


Figure 4.6: Ice thickness distribution (m) at 25,000 years before present for GSM nn9921 showing the location of southern Ontario relative to the ice sheet terminus

In 2008, NWMO awarded a 3-year research grant to Dr. Peltier's research group at the University of Toronto to further refine the GSM model; maintain modelling capabilities in the area of Glacial Systems Modelling; and expand Canadian expertise in this area through the involvement of Postdoctoral candidates and graduate students.

4.3.2 Reactive Transport Modelling and Glaciation

An understanding of far-field geochemical conditions and evolution is fundamental to assessing the long-term performance of a Deep Geological Repository for used fuel. Within the timeframe of greater than 100 000 years necessary to demonstrate repository safety, significant climatic changes will likely occur as a result of glaciation/deglaciation cycles. An understanding of the impact of these glaciations and deglaciation cycles on groundwater at depths relevant to deep geological repositories is needed (Figure 4.7). Reactive transport modelling (RTM) is one potential approach for assessing the geochemical and redox stability of these flow systems at depth.

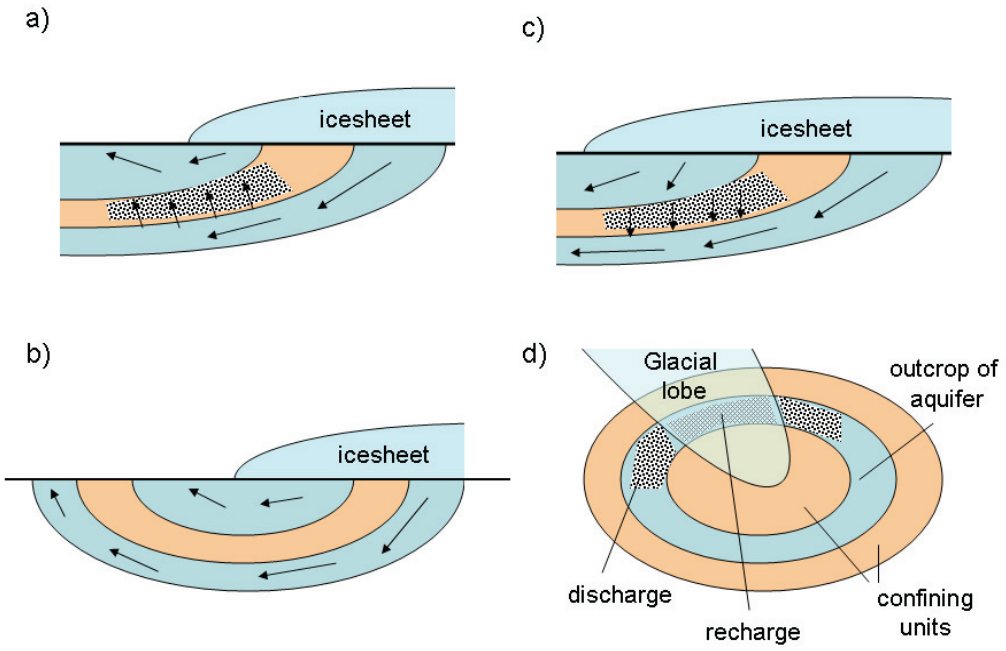


Figure 4.7: Potential mechanisms of melt water infiltration in sedimentary formations: a) ingress through subcrops or outcrops of aquifers and flow through fractured confining units, b) ingress through subcrops or outcrops of aquifers and displacement of resident groundwaters through aquifer and displacement of resident groundwaters through aquifers (after Person et al., 2007), c) vertical ingress through confining units (Siegel, 1991), and d) hypothetical 3D-effects during advancement of glacial lobe. Sedimentary basins as shown in this figure are typically characterized by a spatial extent ranging from 100 - 500km.

Previous studies focused on the influence of glaciation on the stability of redox conditions in crystalline rock using two complementary approaches. One approach involved the application of numerical models to simulate the long-term evolution of hydrogeochemical conditions in fractured crystalline rock (Spiessel et al. 2008; Spiessel et al. 2009). The other investigated the presence or absence of weathering signatures in minerals adjacent to fractures in crystalline rock, to provide information on the maximum depth of penetration of oxygen carried by recharging groundwaters in the past (Cavé and Al 2006; Gascoyne et al. 2004; McMurry and Ejeckam 2002).

In 2007, a state-of-science review of reactive transport modelling in sedimentary rocks was completed (Mayer and MacQuarrie, 2007). The review revealed that reactive transport modelling previously has not been used to assess these processes in sedimentary rocks. However, modelling studies of seawater ingress and CO_2 sequestration in sedimentary rocks show promising results, suggesting that modelling of the geochemical evolution in a 2D-subsection of a sedimentary basin is a realistic goal. In addition, the evaluation of the applicability of current RTMs to assess water-rock reactions under a range of salinities found that none of the currently available codes is capable of capturing all processes of relevance, and it was recommended that the capabilities of the MIN3P code be expanded (Mayer and MacQuarrie, 2007).

A work program was initiated by the end of 2008 to further improve the capabilities of the reactive transport modelling code (MIN3P) to include specific formulations for activity coefficients and ionic strength effects into MIN3P-DENS (Pitzer equations). In addition, model improvements in the MIN3P-DENS code will be developed and implemented. This may include the incorporation of an alternative method for discretization of domains to optimize simulation capabilities for large scale aquifer-aquitard systems in which formations dip gently inward from the basin margins. In addition, simulations will be conducted which will begin to investigate the evolution (including chemical composition, pH and/or redox conditions) during the recharge of glacial waters into aquifer-aquitard systems at sedimentary basin margins.

4.3.3 Hydrogeochemical Synthesis – Field Data Analysis

Several hydrogeochemical lines of evidence indicate that deep groundwaters in the sedimentary rock formations underlying Southern Ontario have remained undisturbed, despite long term perturbations on geologic time scales (Mazurek, 2004). With the exception of groundwaters collected from shallow levels within the sedimentary sequence, high salinities (200-300 g/L Total Dissolved Solids) coupled with the water and strontium isotopic signatures indicate long groundwater residence times. In addition, groundwaters from different formations have distinct chemical and isotopic (water and strontium) characteristics which argue against the occurrence of cross-formational flow in most areas since the time of burial diagenesis of the sedimentary formations. These observations are based primarily on a geochemical data set for 14 boreholes in southwestern Ontario published by McNutt et al. (1987) and Frape et al. (1989). However, an extensive, unpublished geochemical database has been collected during research conducted over 25 years at the University of Waterloo.

This hydrogeochemical synthesis expands the published geochemical database for groundwater from sedimentary formations underlying southwestern Ontario and eastern Michigan to include previously unpublished geochemical information. Chemical and isotopic (δ^3H, δ^2H, δ^{18}O and $^{87/86}$Sr) analyses for more than 200 groundwater samples were compiled to characterize groundwater in three-dimensions on a regional basis (Figure 4.8). In 2007, the evaluation of evidence relating to the evolution and stability of the groundwater systems over geological time scales continued, through a synthesis of the database with published geological, hydrogeological and geochemical literature.

In 2008, the comprehensive geochemical database including both previously published and unpublished chemical and isotopic analyses for groundwaters from the sedimentary formations underlying southwestern Ontario was completed (Hobbs et al, 2008). This database was used to evaluate the chemical and isotopic evidence for depth of penetration of glacial waters into the sedimentary sequence in the past. In addition, cross-formation flow between formations deep in the stratigraphic section was assessed, including any possible relationships with major structural features, as well as any evidence for mixing of groundwaters.

Two geochemical systems are recognized at the regional scale. The first is a shallow system (<200 meters below ground surface) containing fresh through brackish waters with stable water isotope (δ^{18}O, δ^2H) signatures consistent with mixing of dilute meteoric or cold-climate (glacial) waters with more saline waters. The second is an intermediate to deep system (>200 meters below ground surface) containing predominately brines associated with hydrocarbons in reservoirs with elevated TDS values (200-400 g/L). The stable isotopic signatures (δ^{18}O and

δ^2H) of these waters are typical of sedimentary basin brines (TDS > 100 g/L) in that they are enriched relative to the Global Meteoric Water Line. In addition, the stable isotope signatures of waters from formations of different ages and lithologies (e.g. carbonate versus sandstone) are observed to cluster in distinct ranges, which suggests that cross-formational flow is limited. The chemical compositions of these groundwaters are consistent with evolution of the groundwaters by the evaporation of seawater past halite precipitation. Increased concentrations of Ca and decreased Mg concentrations relative to seawater are consistent with dolomitization reactions between these waters and calcite within the carbonate formations.

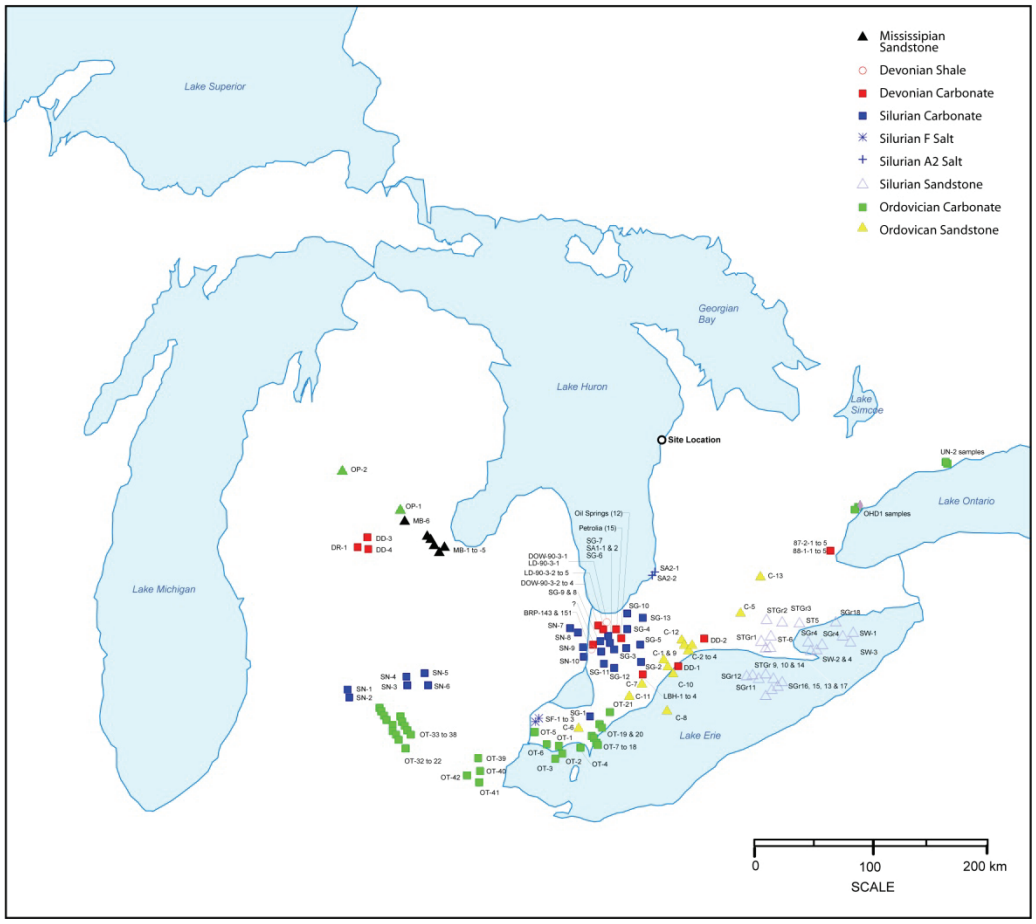


Figure 4.8: Map showing the sampling locations for fluids collected from the sedimentary formations in southwestern Ontario and in central and eastern Michigan, USA (modified from Frape et al., 1989)

4.3.4 Fault Reactivation and Glaciation

Because glaciation and deglaciation cycles are known to have an influence on regional stress regimes and thus on crustal fault stability, a study was initiated in 2008 in collaboration with Dr. Patrick Wu of the University of Calgary to summarize current knowledge and understanding of the influence of glacial cycles on the evolution of regional stress regime and seismicity. This

study includes the review of methodologies available to analyze the behaviour of fractures and faults at all scales in both porous and tight rocks under glacial-deglacial-interglacial cycles. It also examines the spatial and temporal evolution of stresses in the lithosphere during such glacial cycles and, as well as, the applicability of various rock material failure criteria and virtual fault assumptions in fault reactivation analysis. Figure 4.9 shows the fault stability within the lithosphere during glacial loading. A state-of-knowledge report will be issued in 2009.

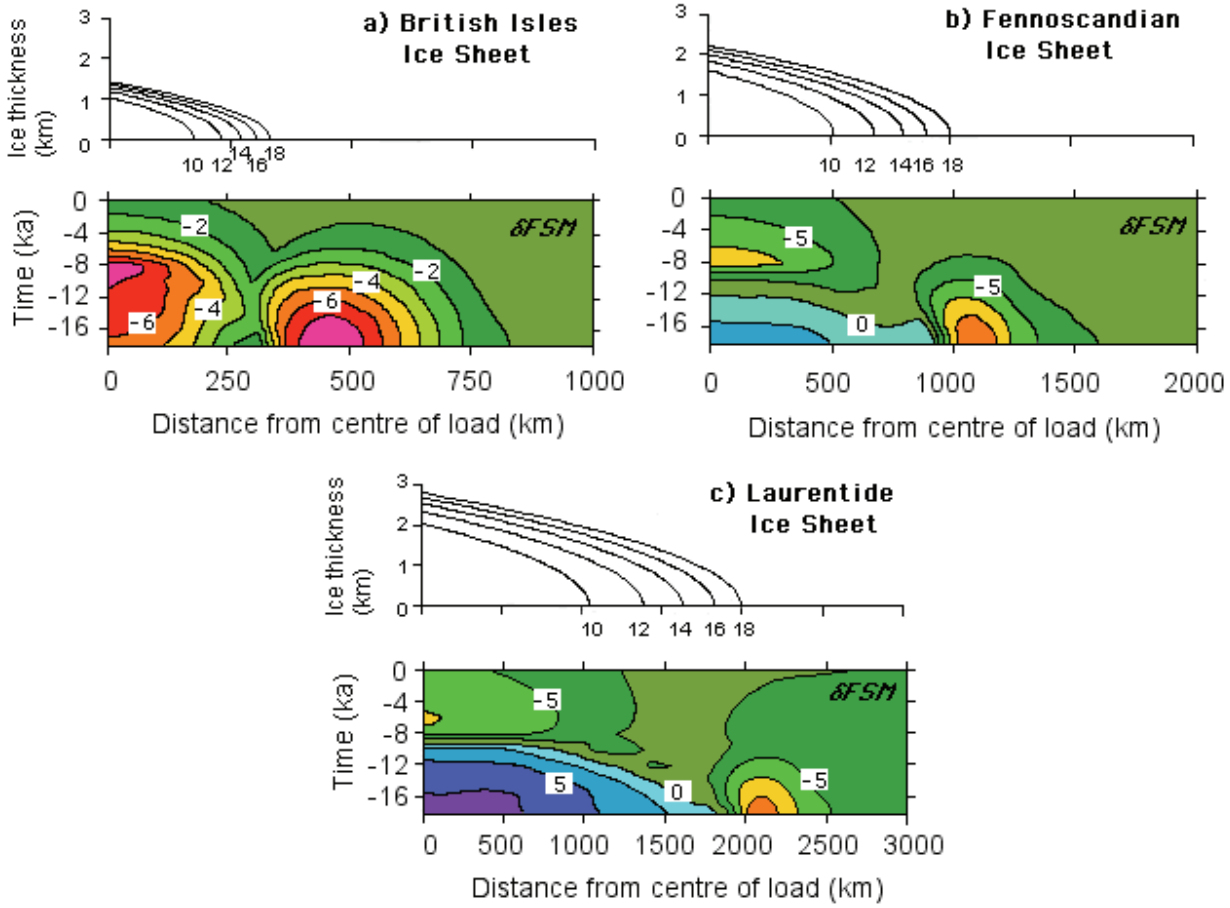


Figure 4.9: Changes in ice thickness and fault stability (δFSM) as a function of time and radius from the center of an axisymmetric parabolic ice sheet; no tectonic stress included (after Johnston et al., 1998)

4.3.5 Impact of Glaciation on Sedimentary Formations

In 2008, a work program was initiated to complete a state-of-knowledge review of glaciation impacts on sedimentary rock formations with the view to assess the resilience of deep groundwater flow systems to physical and chemical perturbations at depths and over timeframes of relevance to a deep geological repository. The state-of-knowledge review, lead by Dr. Mark Person of New Mexico Institute of Mining and Technology, will build on a previous study of the effects of glaciation on groundwater flow systems of North America (Person et al. 2007), and will emphasize numerical modelling and field studies which consider the role of glaciation on deep subsurface flow and transport processes. This review will have a broad

geographic coverage, beyond that of North America, and will also consider the coupling between various hydrologic, geomechanical, geochemical, and thermal transport processes associated with glaciation.

4.3.6 Sub-Regional Shield Groundwater Flow System Analysis

Research to further the understanding of groundwater flow system evolution and dynamics in crystalline shield environments is being conducted in collaboration with the University of Waterloo. The principal focus of the research is to develop numerical geoscience tools and methods to characterize groundwater flow systems during the Quaternary, in order to investigate the long-term performance of a deep geological repository. This is achieved by using numerical methods to test descriptive conceptual geosphere models, as well as to develop methodologies that assess the influence of site characterization uncertainties on numerical groundwater flow and transport predictions.

Previous sub-regional shield groundwater flow studies (Sykes et al., 2003, 2004 and Normani et al. 2007) provided insight into the influence of a number of geosphere properties on deep groundwater flow dynamics and evolution. The studies considered variable salinities, multiple realisations of Discrete Fracture Networks and variable fracture zone permeability, width and porosity. The studies also provided a better understanding of the impact of glaciation on deep groundwater flow systems in Canadian Shield settings. A novel approach based on Mean Life Expectancy (MLE) was used as a performance measure to assess the impact of the various site characteristics considered.

In 2008, NWMO awarded a 3-year contract to the University of Waterloo to further the understanding of the factors influencing the evolution of deep groundwater flow systems in Canadian Shield settings, including the influence of climate change. The scope of the sub-regional modelling program examines the following geosphere features and properties:

- Variable density simulations
- Hydromechanical coupling
- Comparison of MLE, particle tracks and transport travel times
- Boundary condition case studies
- Sub-gridding and sub-timing
- Temperature and change of state
- Enhanced permeability at fracture intersections

The effects of density dependent flow, mechanical coupling and fracture permeability characterization on paleoclimate simulations are demonstrated in Figure 4.10 and Figure 4.11 through the use of a conservative tracer recharging from the surface. In Figure 4.10, glaciation scenario n2778 was simulated with the inclusion of brine and density dependent flow, actual loading efficiency for mechanical coupling and median fracture permeability with depth. Figure 4.11 displays the results from groundwater simulation of glacial scenario n2778 without brine and density dependent flow, without mechanical coupling and a uniform fracture hydraulic conductivity. The depth to which the tracer is able to recharge in each scenario demonstrates the importance of accurate characterization of the density dependent flow, hydromechanical coupling and fracture permeabilities. Without the brine, mechanical coupling and depth dependent fracture permeabilities, the tracer is able to make its way to the bottom of the model. By including the brine, mechanical coupling and depth dependent fracture permeabilities, the tracer remains in the upper regions of the model domain.

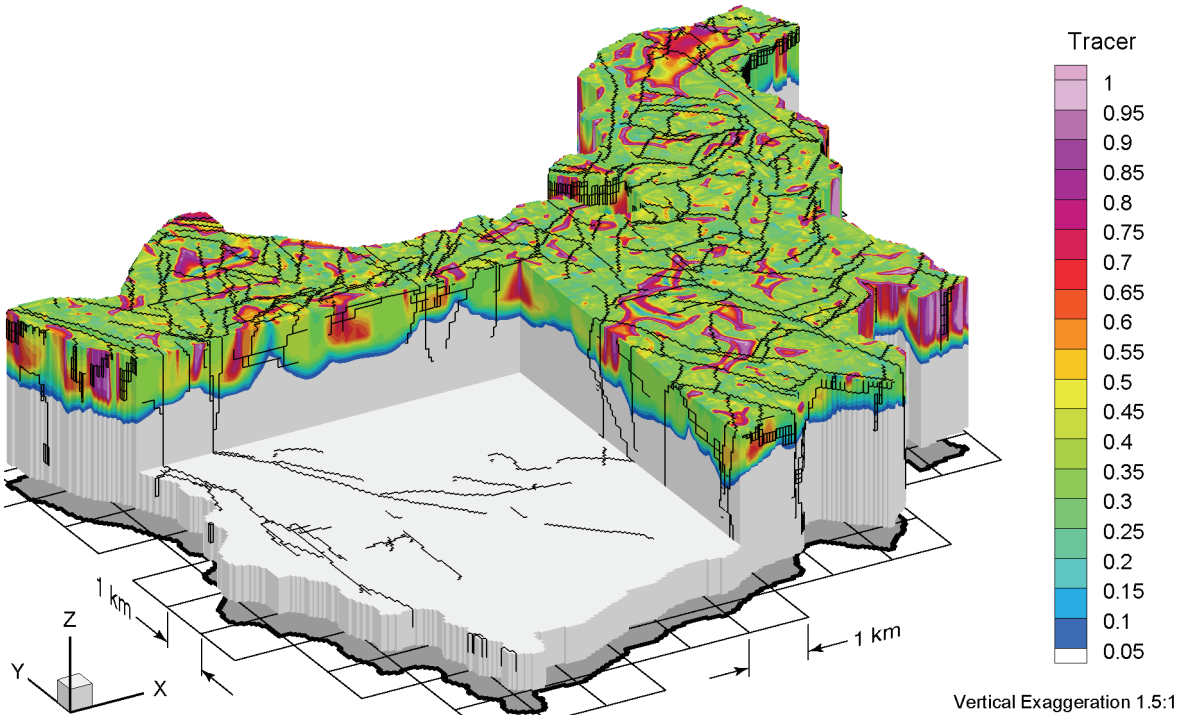


Figure 4.10: Block cut view of tracer for scenario n2778 with brine, actual loading efficiency and median fracture permeability with depth

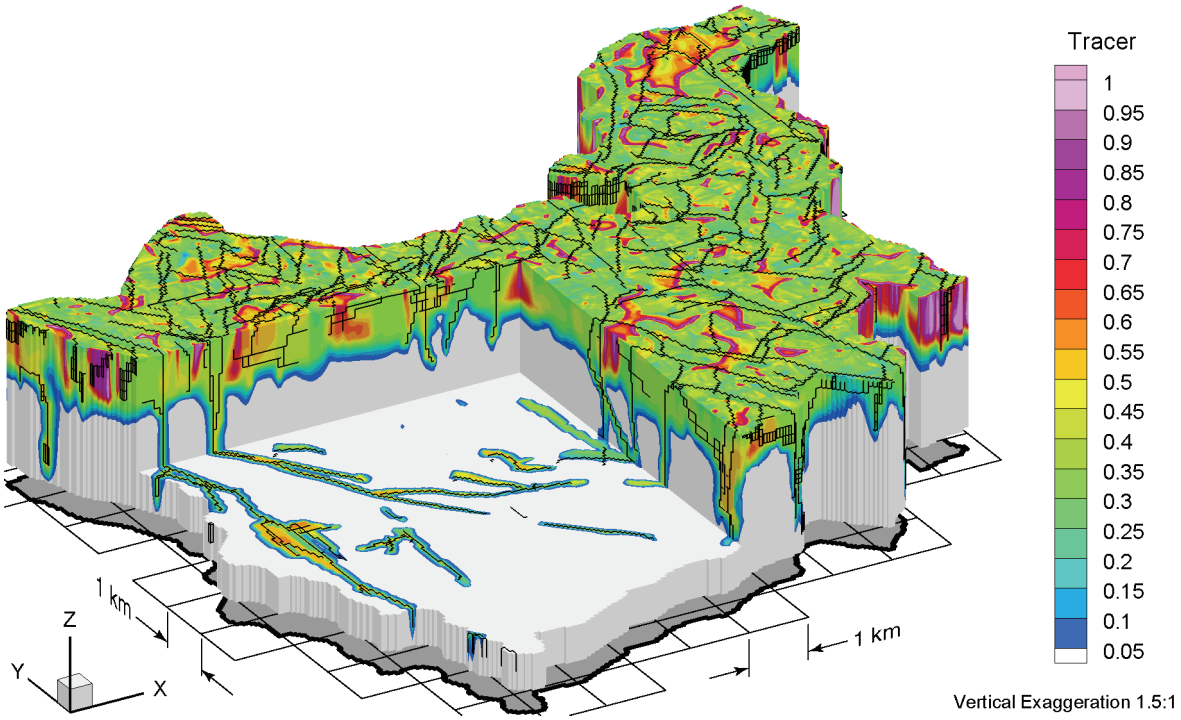


Figure 4.11: Block cut view of tracer for scenario n2778 with no brine, no mechanical loading, uniform fracture hydraulic conductivity

The numerical tools and methods being developed are also being used to perform illustrative safety assessment (section 5.3).

4.4 NUMERICAL TOOLS AND METHODOLOGIES

4.4.1 Hydromechanical Enhancements to FRAC3DVS-OPG

A host rock for a potential deep geological repository will be subjected to many stresses over the course of the repository lifetime. These stresses include the in-situ stress of the rock, stresses induced during the excavation of the repository, thermomechanical stress and finally stress due to glaciation. In the event of glacial loading, upwards of 3 km of ice may be present on the landmass, the stress from which will be transmitted to the geosphere and will impact both the rock matrix as well as matrix fluids. In a fractured crystalline environment, the stress from a glacial load, when applied to the sub-surface can cause changes to the hydraulic properties of the rock mass, in both the unfractured matrix and along fracture planes. These changes to the hydraulic properties of the rock mass could potentially alter the groundwater flow pattern, affecting paths of radionuclide transport.

Historically in FRAC3DVS-OPG, an equivalent column of freshwater has been used to represent the mechanical loading effects due to a glacier. Rather than applying a stress due to the glacial load, the glacial stress was converted to an assumed hydraulic head. However, results from the DECOVALEX task E project (Chan and Stanchell, 2008) found that the increase in hydraulic head due to glacial loading using hydromechanical coupling was relatively uniform in the vertical direction, which was in contrast to what occurred when using an equivalent column of water in a non-coupled flow model.

In FRAC3DVS-OPG, the current implementation of hydromechanical coupling is limited to the case of purely vertical strain with lateral constraints (Guvanasen, 2007); i.e. in the case of glacial loading, the increase in stress is limited solely to the volume of rock directly beneath the glacier (Figure 4.12a). However, increased stresses due to a glacier are not limited to the volume of rock directly beneath the ice, but can develop beyond the glacial front caused by Poisson effects (Figure 4.12b). The effect of glacial stress on changes in hydraulic head can be seen in Figure 4.12c, for both the case of vertically constrained loading, as well as coupled loading with Poisson effects. The assumption of purely vertical loading will cause the hydraulic head to increase to a higher level than the increase due to the loading with Poisson effects. The increase in hydraulic head will also occur much later in time. Based upon this observation, it was decided that in order to more accurately describe the hydromechanical and thermohydromechanical effects, a module would be added to FRAC3DVS-OPG to handle fully coupled hydromechanical processes. The new module will be developed based on the thermohydromechanical formulation of Guvanasen and Chan (2000), and the equivalent poroelastic medium formulation of Guvanasen and Chan (2003). The module will be based on the Galerkin finite-element method in conjunction with the weighted-residuals technique.

4.4.2 FRAC3DVS-OPG Quality Assurance

The increasing importance of FRAC3DVS in repository performance and safety assessment has made it essential that the code be maintained, modified, tested and documented in a formal and disciplined manner. With this objective in mind, a work program was created with the University

of Waterloo to ensure that a version of FRAC3DVS, entitled FRAC3DVS-OPG, meets the relevant quality assurance requirements for modifying and maintaining software. Specifically in 2007, a peer review of a draft FRAC3DVS-OPG QA document, which includes a theory manual, a validation report and a user manual, was completed.

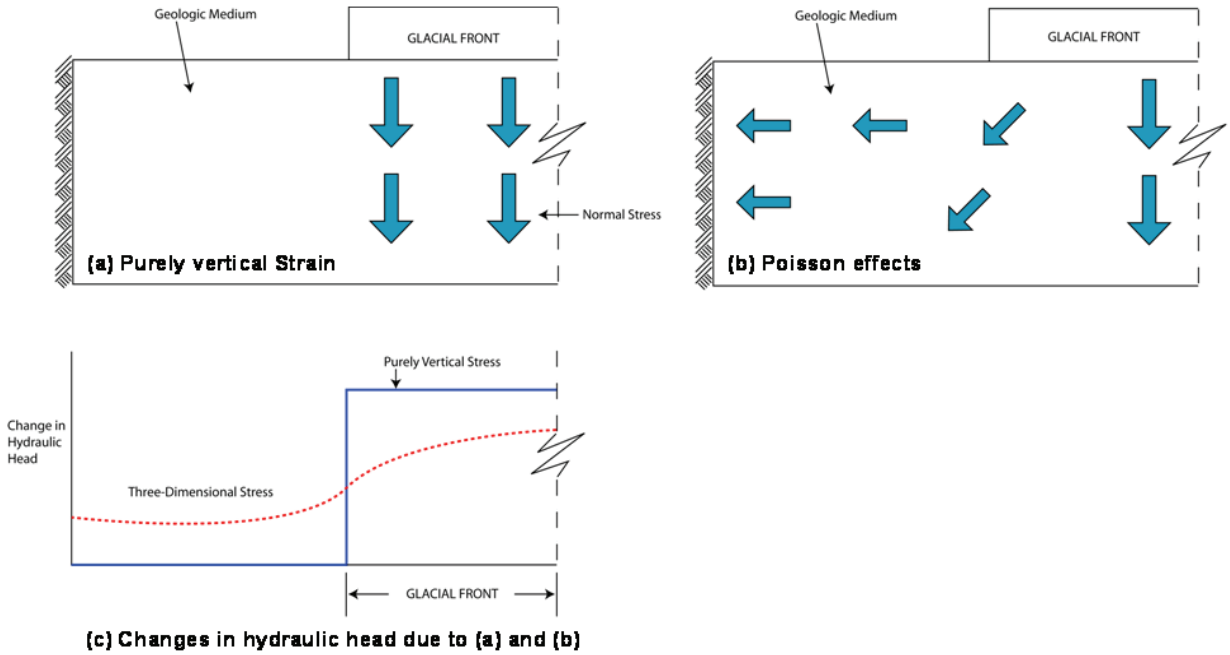


Figure 4.12: Comparison between purely vertical strain and a general 3D hydromechanical coupling scenario

The QA work program ensures that any code modification and development occurs in a traceable, documented fashion and that each new version of the code is accompanied by an appropriate version tracking record. FRAC3DVS-OPG Version 1.1.0 was released in 2008.

4.4.3 Application of COMSOL Multiphysics Code for Coupled THM Modelling

Modelling of coupled thermal-hydraulic-mechanical (THM) processes is required to properly understand and simulate far-field geosphere responses to long-term climate change events, in particular those associated with glaciation. The NWMO's technical research program recently completed Task E of the international, collaborative, coupled THM modelling project DECOVALEX THMC. This task involved the application of the numerical code MOTIF in a study of the subsurface processes that control groundwater flow and stress changes associated with time-varying glacial boundary conditions on a subregional scale, 1.6-km deep, fractured crystalline rock flow system (Chan and Stanchell, 2008). In a continuing effort to maintain and expand expertise in coupled process modelling, a work program was initiated in 2008, lead by researchers at McGill University's Department of Civil Engineering and Applied Mechanics, involving a preliminary and systematic evaluation of the COMSOL Multiphysics finite element based package as an effective and reliable tool for undertaking coupled THM modelling of far-field geosphere processes relevant to a deep geological repository for used nuclear fuel.

The initial phase of the this work program involves calibration of the computational accuracy of the COMSOL-MULTIPHYSICS code through the examination of linearized problems dealing with TH, HM and THM processes separately and to extend these calibrations to both one-dimensional (Part 1) and axisymmetric (Part 2) problems for which analytical solutions are available. A further objective of the work program is to use the COMSOL code to examine more complex problems directly related to long-term used fuel management. The exact solutions available for this class of problems are limited; as such, the emphasis will be on selecting problems that are suitable for inter-code calibrations based on the ABAQUS code. The current work program is scheduled for completion in 2009 with the preparation of a final summary report.

4.5 INTERNATIONAL PROJECTS

4.5.1 Quarried Block Experiment – Bentonite Colloid Transport

The goal of the Colloid Transport Project is to try to gain insight into the potential and significance of erosion of clay-based buffer and backfill materials if dilute water was able to reach a Deep Geological Repository (DGR), such as in a glacial melt water intrusion scenario. This experiment is being undertaken collaboratively with SKB in support of their bentonite colloid program and also the in-situ Colloid Formation and Migration (CFM) experiment being planned at the Swiss Grimsel Test Site.

In 2008, NWMO and SKB initiated an experimental work program at Atomic Energy of Canada's (AECL) Whiteshell Research Laboratory to undertake a laboratory-scale experiment to study bentonite erosion from compacted bentonite borehole plugs intersecting a natural fracture, and the subsequent transport behaviour of bentonite colloids in the fracture. This experiment would leverage the experience gained by AECL and NWMO during the completion of past migration experiments using both bentonite and latex colloids and performed in the Quarried Block (QB) sample, a 1m x 1m x 0.7 m block of granite containing a single, well characterized, through-going, sub-horizontal, variable aperture fracture (Vilks and Miller, 2006). The experimental plan called for an initial mock-up test in a transparent synthetic fracture (Figure 4.13) to test the preparation and installation of a bentonite plug in a borehole intersecting the fracture, to provide insight on plug expansion, gel propagation and erosion mechanisms, and to determine if fluorescent latex colloids mixed in the bentonite plug could serve as a suitable indicator of bentonite colloid behaviour in a fracture. The findings of the mock-up test would be used for planning the actual bentonite erosion experiment in the Quarried Block.

The protocol for the mock-up tests included using different bentonites, water chemistries, latex colloid diameters, flows rates, fracture apertures and fracture angles.

The results from a series of mock-up tests provided a valuable contribution to the CFM project and resulted in significant changes to the design of the final block-scale test. The findings of the mock-up tests (1) demonstrated that latex spheres can be used as a marker for bentonite erosion (Figure 4.14), (2) showed that mobile bentonite colloid concentrations were significantly less in Grimsel water compared to deionized water, (3) that gravitational forces affect bentonite erosion and transport (Figure 4.15), and (4) bentonite deposits may alter flow in fractures.

Bentonite erosion and transport experiments in the Quarried Block fracture will be completed in 2009.

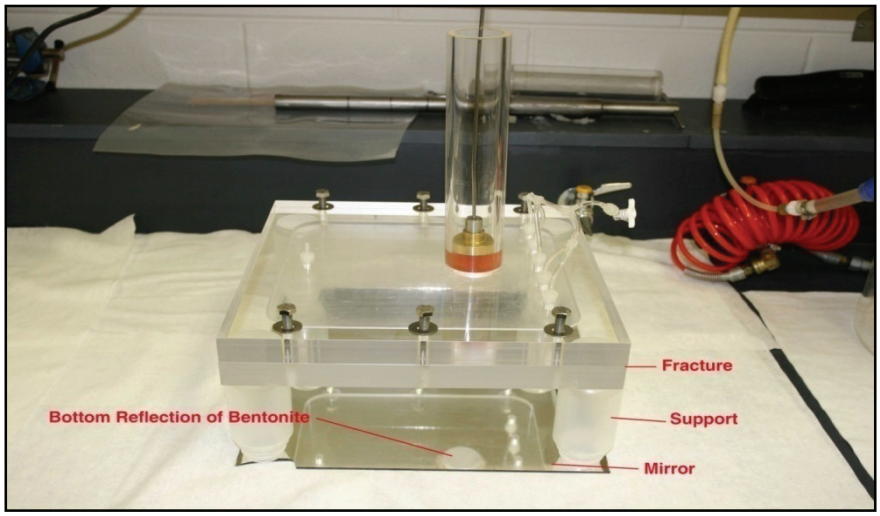


Figure 4.13: Mock-up of fracture and borehole intersection showing inlets on the right and outlet on the left, and borehole packer to contain the bentonite plug

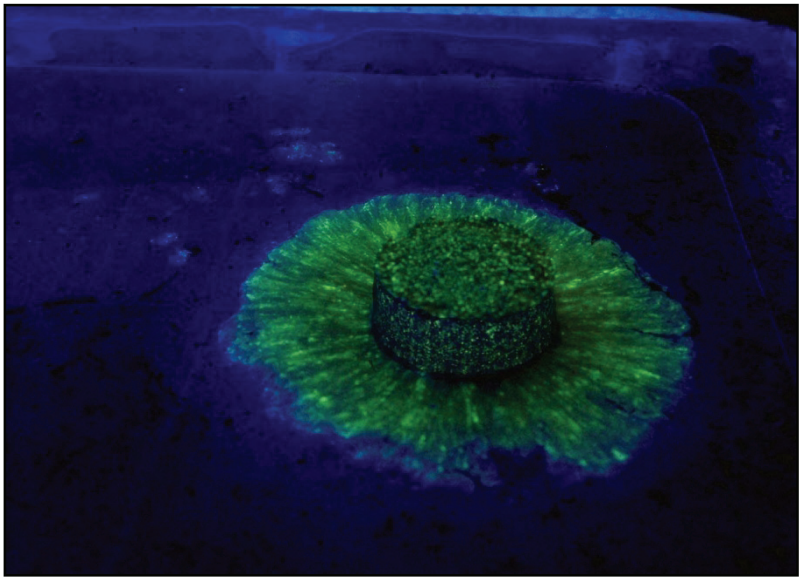


Figure 4.14: Uniform distribution of fluorescent latex spheres within the bentonite visualized during post-test analysis

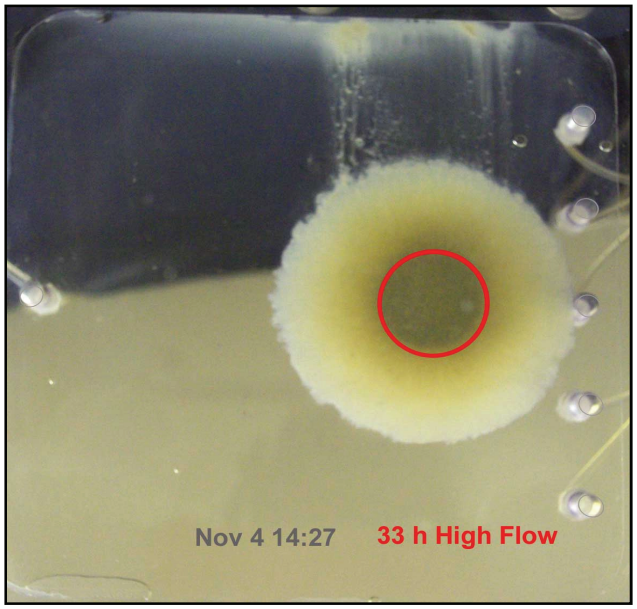


Figure 4.15: View from the bottom of the mock-up showing expansion and movement of Na-exchanged bentonite into a 1 mm fracture under high flow (44 mL/h) from right to left; fracture down dip was 15 degrees to top of page

4.5.2 Äspö Modelling Taskforce

Canada is participating in the Äspö Modelling Task Force's Task 7 in collaboration with a modelling team from the Université Laval (Québec). Task 7 involves the numerical modelling of hydraulic responses in the fractured crystalline rock environment located on Olkiluoto Island in Finland. A large data set is available associated with investigations for Posiva's ONKALO underground rock characterization facility. The task force includes modelling teams from Finland, Sweden, Japan and South Korea. Task 7 modelling activities have been subdivided into two related tasks: 1) 7A was focused on simulating a long-term pump test conducted in borehole KR24, which intersected a domain of several large, interconnected, fracture zones; and 2) Task 7B considers smaller volume of an approximately 500 by 500 m^2 region surrounding a group of boreholes KR14-18 with a borehole separation on the order of 10 m. The modelling tasks involve simulating hydraulic responses in a series of interference tests completed at a block scale and in so doing quantify the reduction of uncertainty in the properties of the fracture network and further assess the contribution of Posiva Flow-logging (PFL) to the characterization of the rock mass between the large fracture zones.

Activities in 2008 focused on completion of Task 7A and initiating Task 7B modelling. Meetings included one task force meeting (TF#24 hosted by SKB at the Äspö Hard Rock Laboratory in Sweden) and one modellers meeting (held at University of Oxford in the UK). Reporting included final reports by modelling groups summarizing their 7A modelling approaches and results, as well as an evaluation report by the secretariat compiling and evaluating the results from all modelling groups.

The 2008 modelling activities for 7B focused on implementing and testing an approach to represent the heterogeneity of the geosphere using available site characterization data sets. The Laval modelling team has adapted a transition probability-based approach with Markov

chains (T-PROGS) to stochastically generate multiple realizations of equivalent porous media based on rock facies of variable fracture densities. Compilation of the data sets from the KR14 to KR18 boreholes, as well as 10 additional surrounding boreholes, resulted in the relationship between hydraulic conductivity and fracture density shown in Figure 4.16. This relationship can be used as an initial estimate of hydraulic conductivity distribution within the modelled domain, which is then further refined through inverse modelling using measured hydraulic test responses.

In 2009, the Laval modelling team will continue to refine the application of T-PROGS to stochastically generate multiple realizations of equivalent porous media and complete the hydraulic simulations necessary to address the 7B performance measures development by the task force secretariat. A final Task 7 report is expected in 2009.

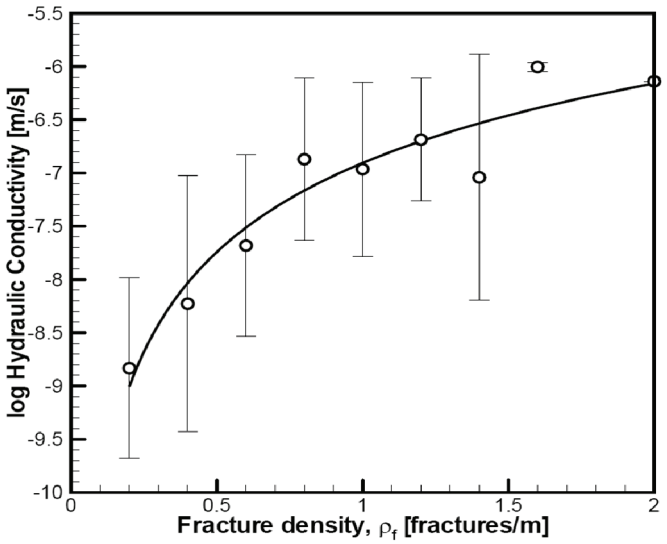


Figure 4.16: Preliminary relationship of hydraulic conductivity versus fracture density resulting from compilation of KR-14 to KR18 and surrounding borehole data sets

4.5.3 OECD/NEA AMIGO Project

The OECD/NEA Approaches and Methods for Integrating Geologic Information in the Safety Case (AMIGO) project was initiated in 2003. The purpose of the project was to provide a forum for the exchange of international information and experience on the use of geoscience information in the development of a safety case for a deep geological repository.

During the last decade considerable experience has been gained internationally with the collection, synthesis and presentation of multi-disciplinary geoscience data to describe existing site-specific conditions and the evolution and integrity of the far-field with important relevance to repository design and safety. This report summarizes the results of a questionnaire circulated to AMIGO participants to capture elements of that practical experience and to collect together current geoscience knowledge and reasoning that supports a safety case. The information is pertinent to long-term radioactive waste management programs which must consider safety

over time frames extending up to 1,000,000 years. Specific goals of the AMIGO questionnaire were to:

i) collect examples of geoscientific lines-of-evidence that directly support or convey confidence in the performance of the repository in varied geologic settings;

ii) consider techniques used for effective communication of geoscientific reasoning and perspectives that support the safety case for a deep geological repository;

iii) identify methods and procedures that provide the geoscientific basis for the safety case, notably the geosynthesis or integration of multi-disciplinary geoscientific information and approaches that can constrain non-uniqueness and uncertainty in the description of the geosphere; and

iv) explore methods related to planning and organizing, to improve the manner in which geoscience information is collected and communicated.

Participants in the questionnaire came from 17 organisations representing both implementing organizations and regulatory agencies from 12 countries, and also representing abroad cross section of national programs with a variety of repository concepts in different host rocks and at different stages of development, from conceptual studies to repository siting and licensing. Their responses have been structured into two primary sections in the report.

The first section summarizes the geoscience reasoning and use of multiple lines of evidence underlying quantitative and qualitative arguments related to the long-term behaviour of the geosphere and how it might influence repository performance. Over 30 examples are documented that cover experience and practice in sedimentary and crystalline settings. While the majority of the examples are drawn from implementing bodies, others represent regulatory remarks or observations on the usage of geoscientific arguments. The topics are site-specific and wide ranging, and include groundwater age and residence times, long-term climate perturbations, sorption and matrix diffusion, diffusion dominant transport regimes, preferential groundwater pathways, depth of recharge penetration, geomechanical stability, self-sealing properties, seismicity, erosion and uplift.

Taken together, these examples reveal a commonality in international programs toward the combination of multidisciplinary evidence to constrain or bound interpretation of geosphere behaviour and to better explain concepts of repository isolation and safety. The examples serve the safety case directly, for example by providing information or data for models used in quantitative evaluation of safety, or indirectly, for example by providing evidence to support model assumptions concerning issues such as site stability.

The second section summarizes responses to a group of questions that examined the emerging role of geosynthesis and challenges associated with communication and management issues. Geosynthesis is the reasoned integration of available geoscience information to construct a comprehensive understanding of the geosphere, often documented in a dedicated volume or part of a safety case. The information can be qualitative and quantitative, and typically derives from many disciplines such as geochemistry, geophysics, hydrogeology, lithology, paleohydrogeology, isotopic analysis, tectonics, structural geology, climate change and glaciation. Paleohydrogeologic arguments are particularly important in discerning the past and concluding or extrapolating about the future stability of the geosphere. This understanding leads to a “conceptual model” of the geosphere, and includes information on uncertainties – using

different lines of reasoning to constrain possibilities. The model supplies the specialized information and data sets pertaining to the geosphere that are needed for the safety assessment and for the design of the engineered barriers. An important outcome from geosynthesis is its contributions to support the safety case with evidence on the potential significance of key processes and mechanisms. The examples described in the first section of this report are largely the products of geosynthesis.

The responses to the questionnaire generally represent a snapshot in time on how geoscience has been applied to explore and bound an understanding of the geosphere, including past evolution and expected future evolution, to better demonstrate confidence in predictions of geosphere performance and long-term safety. It is evident that geoscience provides essential contributions to understanding and communicating the role of the far-field in a repository concept and to the development of technically defensible estimates of repository environmental performance. The report is available to the public and can be downloaded from http://www.nea.fr/html/rwm/docs/2008/rwm-igsc2008-2.pdf.

4.5.4 Greenland Ice Sheet Hydrology Project

Current hydrological models used to simulate glacial conditions are thought to be based on conservative assumptions. However, there are large uncertainties in the current understanding of hydrological and hydrogeological processes during glacial conditions. In 2008 the NWMO, SKB (Sweden) and POSIVA (Finland) established the Greenland Ice Sheet Hydrology Project to improve scientific understanding of the effects of a continental-scale ice sheet on groundwater flow and chemical compositions at potential repository depths. The Greenland ice sheet is considered to be the best analogue for glacial conditions during future glaciations in Canada.

The Greenland project aims to obtain actual observations and measurements of glacial hydrology, groundwater flow and groundwater composition (particularly redox conditions) at the base of a continental-scale ice sheet (Figure 4.17). In 2008, an introductory field campaign was carried out to Kangerlussuaq, Greenland to evaluate potential sites for future drilling activities, to collect baseline information on the geological setting, to collect surface water samples (lakes, springs, glacial meltwaters) and to establish logistical requirements and/or challenges for the planned research. Mapping of the general rock types adjacent to the ice sheet margin was conducted, and geochemical sampling of over 40 lakes and/or glacial outflows proximal to the ice sheet margin was completed. Geochemical sampling included measurements of electrical conductivity, temperature, and pH of the waters in the field, and collection of samples for analysis of major and trace ions and for stable isotopes of oxygen and hydrogen. Two potential sites were identified for drilling of two boreholes to depths of approximately 700 m under the margin of the ice sheet. Field activities and data interpretation will be conducted over four years (2009-2012).

Figure 4.17: Greenland Ice Sheet

4.5.5 Mont Terri Project

In 2008, the NWMO became a participating partner in the Mont Terri Project at the Mont Terri Rock Laboratory in Switzerland. The project involves collaboration with international waste management organizations such as Andra, Nagra, BGR, CRIEPI, ENRESA, GRS, HSK, IRSN, JAEA, OBAYASHI, SCK-CEN and Swisstopo. The project consists of a series of experiments aimed at testing and improving techniques for hydrogeological, geochemical and geotechnical investigations in an argillaceous formation (the Opalinus Clay). The Mont Terri Rock Laboratory is constructed adjacent to the Mont Terri tunnel, one of several tunnels on the A16 motorway. The Opalinus Clay, in which the rock laboratory is found, is part of a large anticline dipping at 45 degrees to the south-east (Figure 4.18).

The NWMO is currently involved in 6 experiments for the Mont Terri Project. These projects are:

- Determination of Stresses (DS)
- Gas path through host rock and along seals (HG-A)
- Iron corrosion in Opalinus Clay (IC)
- Long-term monitoring of pore-pressures (LP)
- Microbial Activity (MA) and
- Mine-by tests (MB)

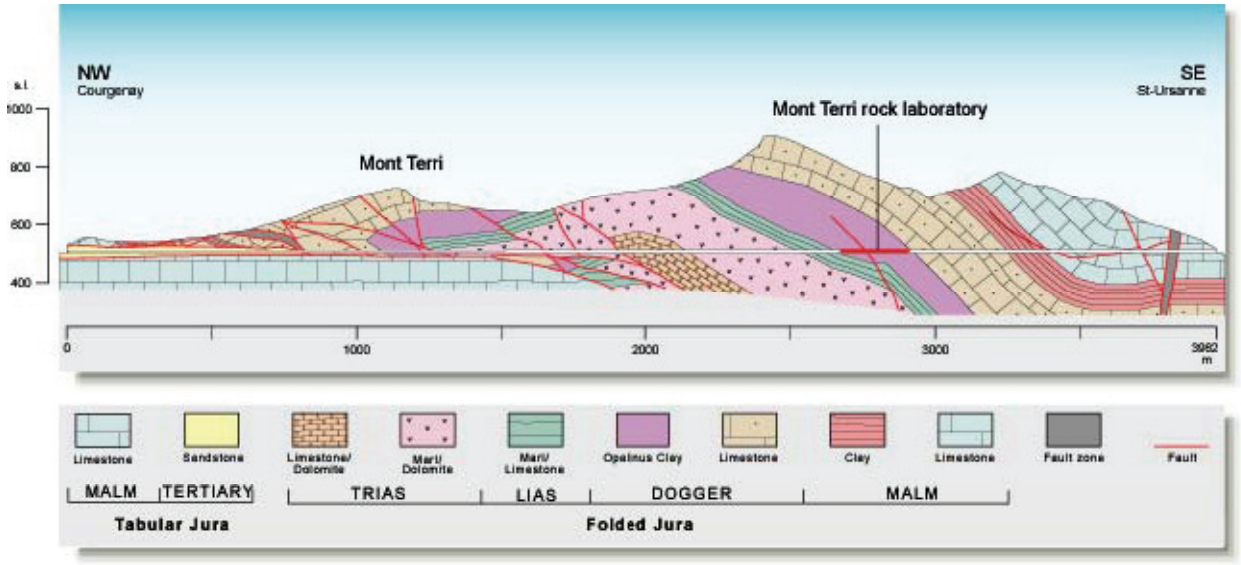


Figure 4.18: Geological cross-section through the Mont Terri anticline including location of the Mont Terri Rock Laboratory (from Hugi et al., 2007)

5. REPOSITORY SAFETY

5.1 ASSESSMENT CONTEXT

The objective of the repository safety program is to evaluate the operational and long-term safety of any candidate deep geological repository in order to assess and improve the safety of the proposed facility. In the near-term, before any candidate site has been proposed, the safety objective is addressed through case studies, and through improving our understanding of important features and processes.

The relevant features and processes are defined by the context for the safety assessment. Specifically, the assessment includes consideration of both normal operation and accidents during facility operation, and of both normal and disruptive scenarios for postclosure performance. It includes assessment of potential impacts on workers and public, and on biota, through both radioactive and chemical hazards, as well as conventional risks during operations.

Key attributes of a deep repository relevant to long-term safety are listed in Table 5.1. Consistent with the nature of the hazard and the containment capabilities of geological repositories, safety assessments are typically carried out for time scales of 1 million years, and therefore features, events and processes that could affect these attributes in Table 5.1 are evaluated on such a timescale.

Table 5.1: Typical Physical Attributes Relevant To Long-Term Safety

- Repository depth provides isolation from human activities
- Site low in natural resources
- Durable waste form
- Robust container
- Clay seals
- Low-permeability host rock.
- Spatial extent and durability of host rock formation
- Stable chemical and hydrological environment

The following sections outline the activities of the Repository Safety work program in 2008. The activities are organised into sections on Model and Data Development, and Case Studies.

5.2 MODEL AND DATA DEVELOPMENT

The objective of this program is to maintain or improve models and data suitable for supporting safety assessment of potential sites and designs. It is divided into five areas discussed in subsections below: waste form, repository model (container, buffer/backfill seals, near-field rock), geosphere model (including shaft seals), biosphere model, and integrated system model.

5.2.1 Wasteform Modelling

The first barrier to release of radionuclides is the used fuel matrix itself. Even if a container fails, most radionuclides remain trapped within the UO_2 grains and are only released as the fuel itself dissolves. Therefore, the rate of fuel dissolution is an important parameter for long-term safety.

UO_2 dissolves extremely slowly under the reducing conditions similar to those expected in a Canadian deep geological repository. However, in a failed container that has filled with groundwater, used fuel dissolution may be driven by oxidants, particularly hydrogen peroxide (H_2O_2), generated by radiolysis of water. The mechanistic understanding of the radiolytic corrosion of UO_2 is therefore important for long-term predictions of used fuel stability.

Within the last several years, dissolved hydrogen gas (H_2) has emerged as a key factor in this corrosion process. Hydrogen is also generated from radiolysis, but much larger amounts are generated as a result of corrosion of the inner steel vessel of the container around the used fuel.

In 2008, a review of the effects of dissolved hydrogen on the corrosion/dissolution of used nuclear fuel was published (Shoesmith 2008). A considerable database of information on the influence of H_2 has been accumulated on a wide range of materials: spent nuclear fuels, unirradiated fuel specimens doped with different quantities of alpha-emitters to simulate the dose rates expected in used fuel at long times, and SIMFUELs, which are unirradiated analogues of used fuel that simulate different degrees of fuel burnup.

These studies indicated that even small pressures of H_2 (0.1 to 1 bar) can effectively suppress fuel corrosion and radionuclide releases from used fuel. Since production of H_2 will commence as soon as waste containers fail and groundwater contacts the carbon steel liner, and H_2 pressures up to 50 bars are anticipated in sealed repositories, this influence of H_2 has the potential to shut down fuel corrosion. The mechanisms proposed to explain this effect were reviewed in detail and it was concluded that the primary reductant leading to protection of the fuel against corrosion is the $H^{\bullet}$ radical species, which can be produced by a number of activation steps, depending on the composition of the fuel and the form of the radiation present (Shoesmith 2008).

The 2008 experimental program on used fuel dissolution, which was carried out at the University of Western Ontario, investigated: (1) the influence of H_2, (2) the influence of fuel composition on the reactivity of UO_2, and (3) the effect of pH. Both electrochemical experiments, typically corrosion potential, E_{corr}, measurements on UO_2 electrodes, and surface analytical techniques were used in the investigations (He et al. 2008a,b; O'Neil et al. 2008). The tests were conducted mainly with unirradiated 1.5%, 3% and 6% SIMFUELs, representing CANDU fuel burnups from about 210 to 800 MWh/kgU. (SIMFUEL is made by doping unirradiated natural UO_2 pellets with non-radioactive elements to replicate the chemical composition of used fuel, including formation of so-called ε-particles – alloys of the fission products Mo, Ru, Tc, Pd and Rh.)

<u>Hydrogen Inhibition</u>

Work in previous years demonstrated the ability of dissolved H_2 to suppress fuel oxidation/dissolution by reaction on galvanically-coupled ε-particles (Broczkowski 2008, Shoesmith 2008). SECM (Scanning Electrochemical Microscopy) confirmed that ε-particles are

catalytic sites for the $H_2/H^{\bullet}/H+$ reaction. Suppression could be achieved with sub-millimolar concentrations of H_2.

In 2007, a series of corrosion potential measurements followed by X-ray photoelectron spectroscopy (XPS) examinations of the surface showed that H_2O_2 and H_2 react synergistically on SIMFUEL electrodes containing epsilon particles. These results suggested that the scavenging reaction $H_2O_2 + H_2 \rightarrow 2H_2O$ is catalyzed on the ε-particles, which protects the UO_2 from oxidation and corrosion. These experiments were continued in 2008 with SIMFUELs containing no ε-particles.

Although H_2 seems to have very little influence on the surface of UO_2 not containing ε-particles, the scavenging of H_2O_2 by H_2 may still be possible on UO_2 in the absence of ε-particles. This is illustrated by the results shown in Figure 5.1. Even in the absence of ε-particles, the presence of H_2 has an effect on E_{CORR}. Further experiments are needed to clarify whether the scavenging of H_2O_2 by H_2 is being catalyzed by the rare-earth doped UO_2 surface. If true, this means that radiolytically formed H_2O_2 could be reduced to H_2O in a used fuel container, rather than driving fuel oxidation.

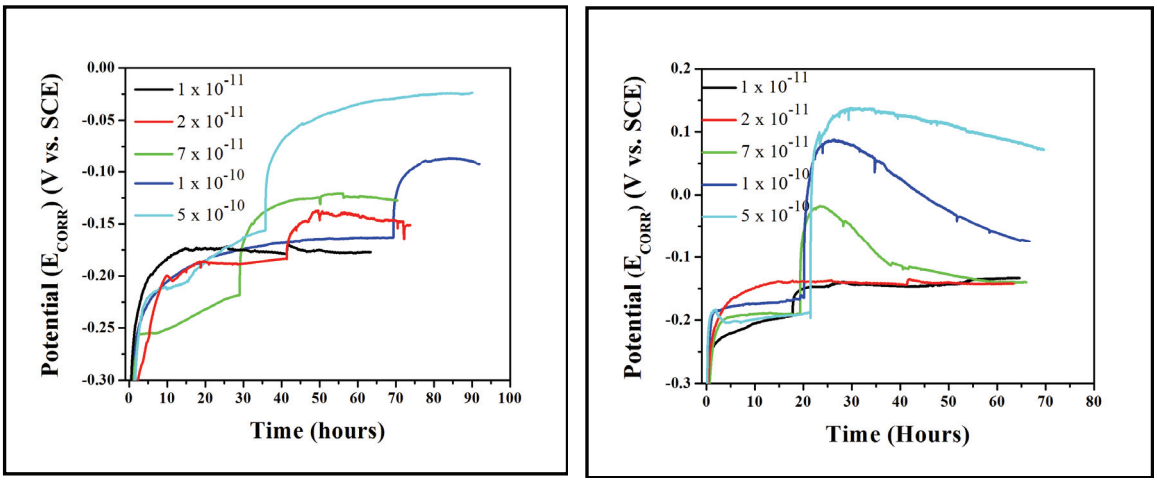


Figure 5.1: E_{CORR} measurement on SIMFUEL with no ε-particles. The changes in the E_{CORR} arising from addition of different concentrations of H_2O_2 are shown for cases in which the solution is being purged with argon (left) or with 95%Ar/5%H_2 (right). The latter low-H_2 purge shows the E_{CORR} levels recovering back to their original levels before H_2O_2 was added.

Influence of Degree of Fuel Non-Stoichiometry on Fuel Reactivity

Non-stoichiometry (x in UO_{2+x}) could exist at grain boundaries of the fuel, where lattice defects concentrate, and affect both the cathodic (H_2O_2 reduction) and anodic (UO_2 oxidation and dissolution) reactions. Also, older fuels may have a higher degree of non-stoichiometry than currently manufactured fuels because fuel sintering was not as effective as today. Thus, it is important to understand the effects of non-stoichiometry on fuel kinetics.

Scanning electrochemical microscopy (SECM) was used to determine the corrosion kinetics of UO_2 fuels with well characterized overall stoichiometries (He et al. 2008a,b). In addition, since the fuel non-stoichiometry causes formation of complicated defect structures (that are distributed non-uniformly within the experimental fuel specimens), the fuel could also be characterized by Raman spectroscopy (He et al. 2008a,b). While such a distribution of defects would not be anticipated in CANDU fuel, these experiments offer a means of characterizing the influence of non-stoichiometry, which would be more narrowly distributed in the grain boundaries in actual fuel pellets. The relative reactivity at different sites on the fuel surface can be determined from analysis of the experimental SECM data (see Figure 5.2). Samples with the largest non-stoichiometry had the widest variations in fuel reactivity.

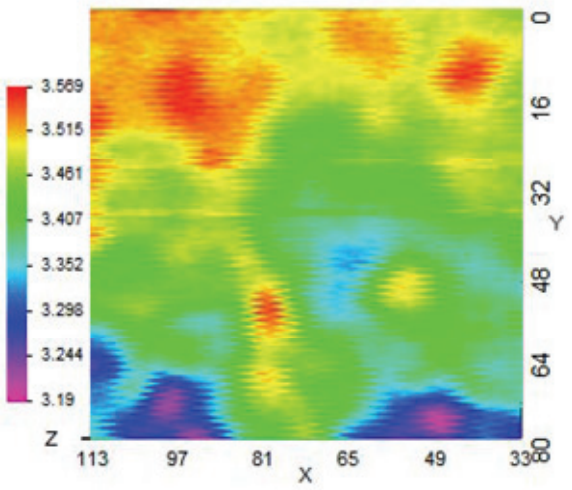


Figure 5.2: SECM map of a $UO_{2.05}$ fuel sample. The colour scale indicates the relative anodic reactivity at the fuel sites: reactive (red) to non-reactive (mauve).

SECM experiments, with fuel samples with different overall stoichiometry (2.00, 2.011, 2.05, and 2.1), indicated that the anodic reactivity of the fuel increases markedly with the degree of non-stoichiometry. Comparison of the SECM rate constants to the intensity of the Raman peak at 450 cm^{-1} (O-U stretch) shows that the reactivity increases as the cubic symmetry of the crystal lattice of the fuel is lost due to increasing non-stoichiometry.

Since the non-stoichiometry in used fuel concentrates at grain boundaries, it can be concluded that grain boundaries could be reactive sites in used fuel. SECM can provide the relative reactivity of the grain boundaries (relative to the fuel as a whole) if the degree of non-stoichiometry at the grain boundaries is known.

The influence of the non-stoichiometry on cathodic kinetics (H_2O_2 +2e- → 2OH-) is currently under study using rotating ring-disc electrodes to study the reactions between UO_{2+x} and H_2O_2.

pH Dependence

Model calculations carried out in 2007 indicated that the development of local acidic sites on the UO_2 surface was possible with strongly oxidizing conditions and deep sites (i.e., pores or cracks). Furthermore, identification of studtite in natural uranium deposits suggests that

acidified peroxide locations can be formed. Consequently, studies of the reaction of H_2O_2 with UO_2 fuel were extended over a wide pH range.

It was found that the mechanism of H_2O_2 reduction does not appear to change with pH down to pH = 4 (Keech et al. 2008). However, at pH values < 4, the mechanism was observed to change and peroxide became more aggressive. Later studies in 2008 indicated that, in fact, this change in mechanism rendering H_2O_2 more aggressive may be achievable up to pH = 6, which is potentially achievable at localized sites in fuel exposed to neutral groundwaters. The details of this change in mechanism remain to be elucidated.

Many of the previous experiments studying the anodic oxidation of UO_2 have been done at pH = 9.5. In 2008, experiments were initiated to determine if the mechanism and rates of anodic dissolution are the same at pH = 8 and pH = 9.5. Initial experiments show that the current versus potential curves at pH = 8 fall within the observed variability of the current versus potential curves measured at pH = 9.5, with the variability mainly arising from variability in the fuel samples. Consequently, it is not expected that a change in pH from 9.5 to 8 would significantly affect the kinetics of the anodic reactions on the fuel surface.

Instant Release Fractions

The instant release fraction (IRF) is an important parameter in the safety assessment of a deep geological repository for used nuclear fuel (Garisto et al. 2005). In 2008, a review was conducted of the NWMO database of instant release fractions for used CANDU fuel. The review concluded that the existing database is likely sufficient for present purposes, but some options for improvement were noted. Important recommendations arising from the review are as follows:

1. The IRFs for Cs and I should be updated to those measured by Stroes-Gascoyne (1996), which are about 2-fold lower than the current values. Since the IRFs for some elements (e.g., Se) are set equal to those of I or Cs, these should also be updated.
2. Calculate average IRFs on the basis of the existing used CANDU fuel in storage, in relation to the linear power rating (LPR) of the fuel. Data indicates that IRFs are low if LPR < 42 kW/m, which is the case for most stored used fuel bundles.
3. The current IRF for Sr-90 in used CANDU fuel is 10-fold larger than for LWR fuel, and new work would be needed to resolve the reason for this difference. However, Sr-90, because of its short half-life, is not an important radionuclide in the safety assessment of a geological repository for used fuel.

The IRF database will be updated in 2009 based on these recommendations.

5.2.2 Repository Modelling

The repository or "near-field" region includes the waste, the container, the surrounding seals and other engineered barriers, and the adjacent host rock. Almost all the radioactivity is expected to be isolated and contained within this area. Repository safety work in this near-field region is aimed at improving our understanding of the transport-limiting processes around a failed container. (Work on container corrosion models was carried out under the Repository Engineering program and is described in Section 3.1.)

Failed container model

The used fuel container is also a primary barrier to release of radionuclides. Initially it provides an obvious barrier by preventing any access of water to the used fuel. Eventually, however, the containers will corrode or fail, and water will be able to enter and contact the used fuel. At this time, residual radioactivity within the used fuel may be released into this water (albeit slowly, for reasons noted in Section 5.2.1), and then could be released from the container.

However the container would still be present, and would still represent a physical constraint on both the rate of water access as well as radionuclide release. The objective of this project is to consider the potential state of a container during this period in order to improve the current model for radionuclide release from a failed container. This work was initiated in 2008.

Radionuclide solubility

The maximum concentration of radionuclides is limited by their solubility in water. Many potentially important radionuclides, such as plutonium, have very low solubilities in water under conditions expected around a deep repository, and therefore are never mobilized into the water in large amounts.

Solubilities are generally calculated using thermodynamic models which incorporate data for radionuclide elements, as well as for the water composition and key minerals. There are a number of widely used thermodynamic datasets that support these models, and there is ongoing international work to improve the data.

NWMO continues to support the joint international Nuclear Energy Agency effort on developing thermodynamic databases for elements of importance in the safety assessment of a geological repository for used fuel (Mompeán and Wanner 2003). In 2008, the NEA Thermodynamic Database Project Phase IV was initiated. This phase will see completion of the iron dataset review, update of selected existing datasets (notably, U), and a review of Mo thermodynamic data will be initiated and completed.

NWMO has also been recently active in reviewing solubility data with respect to the effect of salinity. Conventional geochemical solubility models, typically based on the “ion pairing and complexing approach”, are only suitable for solutions with ionic strength up to 0.8 mol/kg. However, some potential deep Canadian groundwaters could be very saline, with ionic strengths greater than 8 mol/kg (Section 5.2.3). For solutions of higher salinity, an approach which is based on “specific-ion interaction” (also known as the Pitzer approach) will provide more accurate results. The problem with the Pitzer approach is that there is generally less data available to support the thermodynamic modelling.

One quality assured dataset with Pitzer data for many species of interest was developed by the Yucca Mountain Project. However, this data is formatted for the EQ3/6 geochemical model. In 2008, this EQ3/6 dataset was converted into PHREEQC format, the NWMO reference geochemical model.

Building on these and other datasets, a project has also been initiated to update the solubilities used by the safety assessment models.

Gas transport through buffer

Corrosion of steel containers will result in the slow generation of gases. The low-permeable clay seal around the container will hold in these gases until sufficient pressure is reached, and then release the gases. The nature of this behaviour is of interest for understanding the behaviour in the near-field around a failed container. To explore this area, a full-scale in-situ test called "LASGIT" was initiated several years ago in the SKB Äspö Hard Rock Laboratory in Sweden.

NWMO is contributing to the gas transport modelling component of LASGIT. All gas transport modelling is being conducted for NWMO by Intera Engineering. Previously, the TOUGH2 two-phase transport code was selected as reference code, and then modified for LASGIT to simulate pressure-induced changes in the properties, such as micro- and macro- fracturing. In 2006 and 2007, the modified code was applied to laboratory experimental data (MX-80-10 conducted by Harrington and Horseman, 2003) and predictive simulations of the LASGIT experiment.

In 2008, modelling of the laboratory experiment was further refined with geostatistical heterogeneous permeability fields. Geostatistical heterogeneous permeability fields provide structure to a randomly generated permeability field, and were generated using Sequential Gaussian Simulation. These heterogeneous permeability fields improved the representation of gas outflow in the model in comparison to a homogeneous model, particularly with respect to the distribution of flow between the upper, middle and lower sinks (Figure 5.3). The results also demonstrated that the gas outflow results are extremely sensitive to the allocation of higher and lower permeability zones, likely due to the use of what are essentially point sources and sinks in the laboratory experiment. The amount, distribution, and timing of outflows were strongly dependent on the local permeability near the injection and sink elements.

Attempts were also made to model the LASGIT experimental results for preliminary gas injection tests conducted in 2007. However, after analyzing the experimental results and examining preliminary model results, it was determined that the pore pressure responses at the rock wall during the hydraulic and gas injection tests conducted in 2007 were either non-existent or probably the result of hydromechanical behaviour. The modified TOUGH2 code was designed to model gas breakthrough due to pressure-induced changes to bentonite properties, but it is not capable of modelling hydromechanical processes. Therefore, the small pore pressure perturbation at the rock wall observed during the preliminary gas injection tests conducted in 2007 could not be modelled with the current TOUGH2-based LASGIT model. However, preliminary modelling highlighted required improvements to the LASGIT model for future modelling of gas breakthrough in the LASGIT experiment, particularly boundary and initial conditions. The preliminary work also indicates that improvements in the representation of injection assemblies and pore pressure sensors may also prove useful.

Future modelling in 2009 will improve the LASGIT model by improving boundary and initial conditions. Assuming the availability of results from hydraulic and gas injection tests to be conducted in 2009, these tests will be simulated.

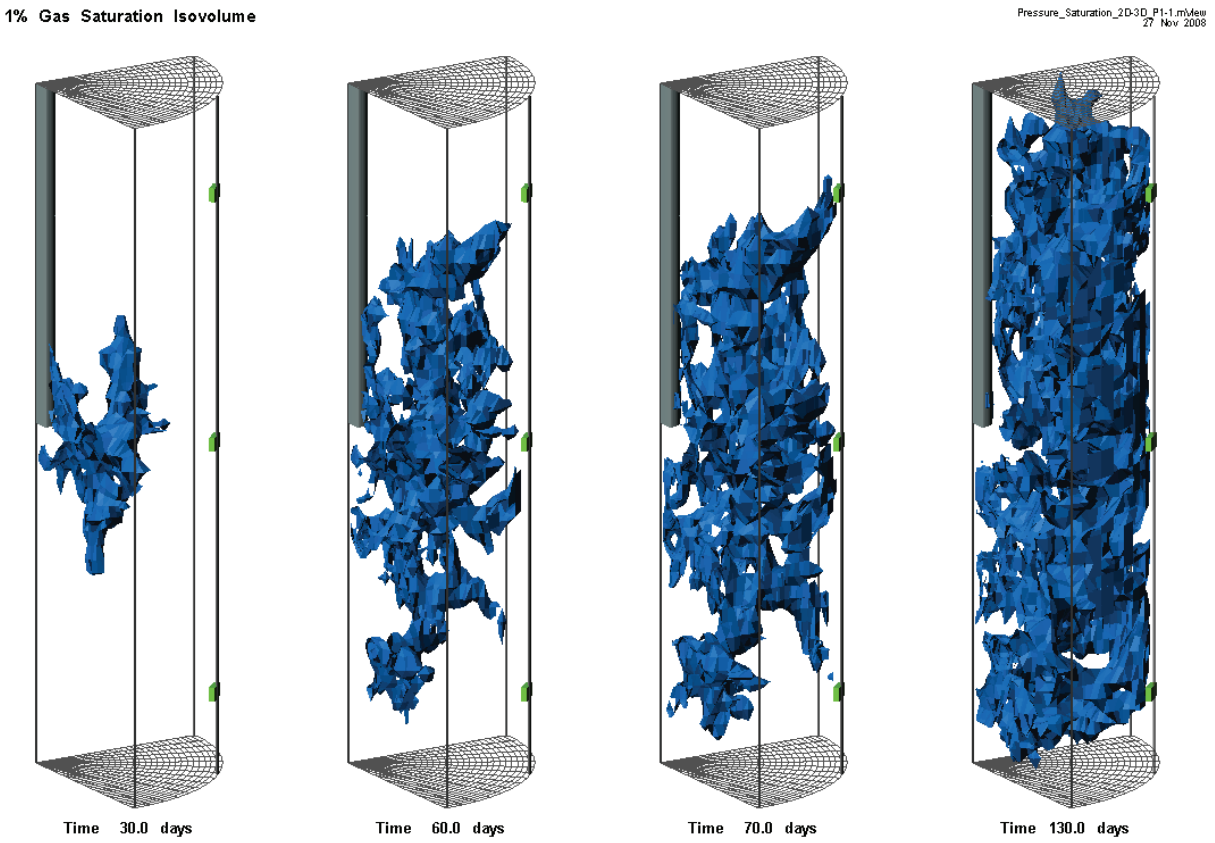


Figure 5.3: Time-varying gas saturation isovolume for heterogeneous permeability simulation. The figure shows the quarter section of the model domain of the laboratory-scale bentonite sample, with the gas injection point at the centre of the sample and three gas sinks (green symbols) at the edge of the sample.

5.2.3 Geosphere Modelling

The development of improved geosphere models is largely carried out under the Geoscience work program (see Section 4). Recent safety assessment case studies have used both detailed geosphere models and system-level safety assessment models. In particular, the Third Case Study (TCS) and TCS/Horizontal Borehole Concept studies (Gierszewski et al. 2004b, Garisto et al. 2005) have used the regional study model similar to that used in ongoing Geoscience numerical studies, and the FRAC3DVS code (see Section 4.4) to provide detailed 3-D groundwater flow and transport analyses. This ensures that the same geosphere conceptual model is being used by both geoscience and safety assessment groups.

Presently there is no specific candidate site or rock type within the Canadian program. In order to further coordinate both modelling and experimental work, an initial set of representative groundwaters were identified, some of which are listed in Table 5.2. These are representative of the types of waters that are likely to be found in suitable deep underground locations in Canada, based on averages from compositions measured in various crystalline and sedimentary rock settings.

Table 5.2: Representative Deep Groundwater Compositions

Rock Type	Crystalline			Sedimentary	
Nominal pH	7.5	7.5	7.5	6.5	6.5
Environment Type	Reducing	Reducing	Reducing	Reducing	Reducing
Nominal Eh (mV)	-200	-200	-200	-200	-200
Solutes (mg/L)					
Na	5,100	3,400	1,900	43,100	37,400
K	50	20	15	3,600	1,750
Ca	15,000	4,800	2,130	57,300	14,700
Mg	200	50	60	9,900	3,900
HCO_3	10	25	70	40	60
SO_4	800	800	1,000	160	460
Cl	34,300	13,800	6,100	199,500	97,400
Br	-	85	-	2,000	600
Sr	20	55	25	900	480
Li	-	0.1	-	9,800	9,800
F	-	2.5	2	8	40
Si	15	3	5	<200	<200
Fe	-	2	1	50	47
NO_3	50	<1	<1	<10	<10
PO_4	-	0.2	<1	-	-
TDS (mg/L)	55,500	23,000	11,300	327,000	167,000

5.2.4 Biosphere Modelling

<u>Iodine in the biosphere</u>

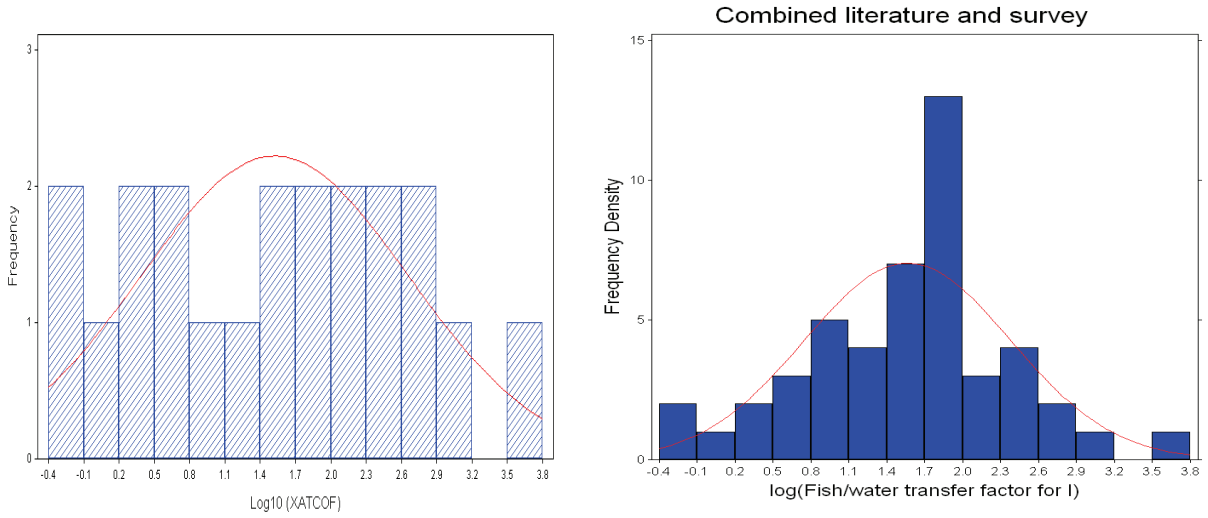
Iodine-129 is an important radionuclide with respect to a potential long-term public dose impact. In 2002, a literature review was completed and key biosphere model parameters were updated for iodine (Sheppard et al. 2002, 2006). The review indicated several areas where further data would be useful.

One reason for the limited database is that it has historically been difficult to measure iodine in the biosphere because of the low sensitivity of standard analysis procedures. In 2006, a technique was demonstrated that allowed natural iodine levels to be measured using relatively standard equipment. Using natural iodine as an analogue, this opened up an opportunity to improve the I-129 dataset by looking at the natural distribution of iodine.

In 2007, this new approach was used to measure key transfer factor data and obtain other ancillary media parameters in the aquatic and terrestrial ecosystems, which are of interest for safety assessment case studies (e.g. fish, wild game, berries). In 2008, the analysis was extended to include farm environments and domestic animals, as well as a small sampling of tundra ecosystem biota (relevant to periglacial conditions).

Areas within a representative portion of the Canadian Shield were subdivided into distinct sampling zones to ensure the survey represented the physiographical variation within the larger sampling area. Initial results show good agreement between measured transfer factor results and plant/soil concentration ratios for iodine compared to those of Sheppard et al. (2002). A multi-year (2007-2009) sampling campaign is currently entering its final year of data collection from a variety of media and regions, with 2009 focusing on agricultural meat samples.

Considerable improvements to the data is already apparent in preliminary analysis of samples from 2007 fish data presented in Figure 5.4.



(a) **(b)**

Figure 5.4: (a) Previous iodine transfer factor database from water to fish; (b) Iodine transfer factor from water to fish including the 2007 NWMO sampling data

Selenium in the biosphere

Selenium is an important element to safety assessment of a repository because Se is both mobile in the environment and readily absorbed by both humans and biota. (It is also essential at low levels.) The extent of Se volatility has been uncertain. If it is volatile, then the air pathway can be important; for example, allowing for a significant reduction in soil and sediment concentration via airborne releases over time.

The results from an extensive literature review of Se volatilization are illustrated in Figure 5.5. It was found that the major factors affecting the volatilization of Se from soils are microbial activitiy, soil moisture content and soil pH.

First, it is thought that while inorganic Se cannot be volatilized, Se-methyl complexes are quite volatile and so microbes have to be present and functional to methylate the inorganic Se and make it volatile. As for soil conditions, drier soil allows volatile Se to pass through the soil pore spaces faster and come from deeper depths, but has an adverse effect on microbial populations. On the other hand, while moist soil favours the microbial habitat and the continual decomposition of organic matter that provides the substrate required by the microbes to

function, volatile Se at depth will become trapped. Similarly, the pH of the soil also controls which microbial species are allowed to flourish and can greatly impact the rate of volatilization. A complex symbiotic relationship exists between optimal microbial and volatilization soil conditions leading to considerable fluxuations (ranging 41000-fold) in soil volatilization rates.

Considerably less data is available for sediments, however the few sources that were found indicated that sediment volatilization rates are generally lower than those for soils, likely the net result of increased moisture. Like the sediments, there is relatively little data for plant volatilization. While the relationship is not well understood, it is believed to be strongly coupled to the soil concentration.

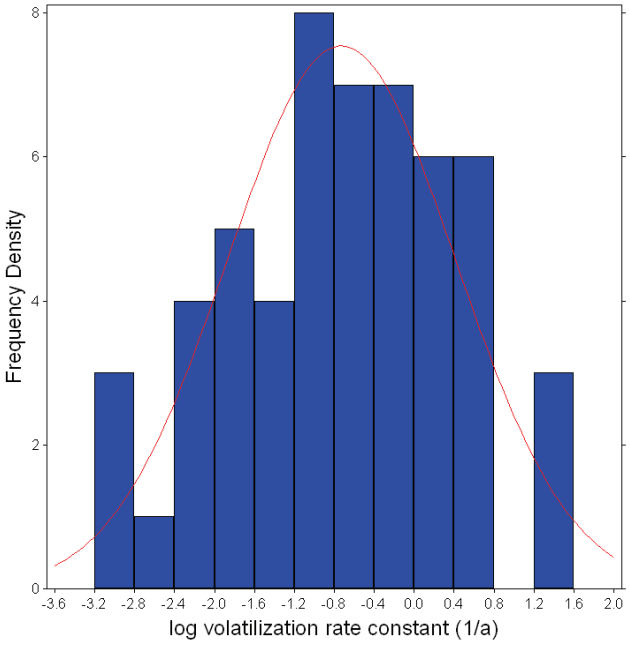


Figure 5.5: Frequency histogram of log volatilization rate constants for soil (a^{-1})

Non-human biota

Previous Canadian case studies on used fuel disposal in a deep geological repository (AECL 1994, Goodwin et al. 1996, Gierszewski et al. 2004b) have focused on potential impacts on humans. The impacts on non-human biota were considered, but not in detail.

Work was completed in 2008 on a screening methodology for assessing the potential postclosure impact of a repository on specific representative non-human biota. The methodology involves the estimation of reference No-Effect Concentrations (NECs) for radionuclides in environmental media to which biota are exposed. In this study, NECs were developed for a set of 12 radionuclides: C-14, Cl-36, Zr-93, Nb-94, Tc-99, I-129, Cs-135, Ra-226, Np-237, U-238, Pb-210, and Po-210. This list incorporates the major dose contributors identified in the Canadian Third Case Study and in other international safety assessments.

The screening would be carried out by comparing estimated radionuclide concentrations to these NECs, which are threshold criteria. Because of the conservative nature of the

assumptions used to derive the NECs, there is confidence that, despite uncertainty in environmental concentrations, there will be no significant ecological effect on biota as long as the NECs are not exceeded. In the event NECs are exceeded, a site-specific Ecological Risk Assessment would be required to determine whether this is due to conservatism in the assumptions, lack of sufficient data or potential real impact.

The screening methodology assessed three representative ecosystems; the boreal ecosystem is illustrated in Figure 5.6. The modeling and the recommended NECs are described in Garisto et al. (2008a, 2008b).

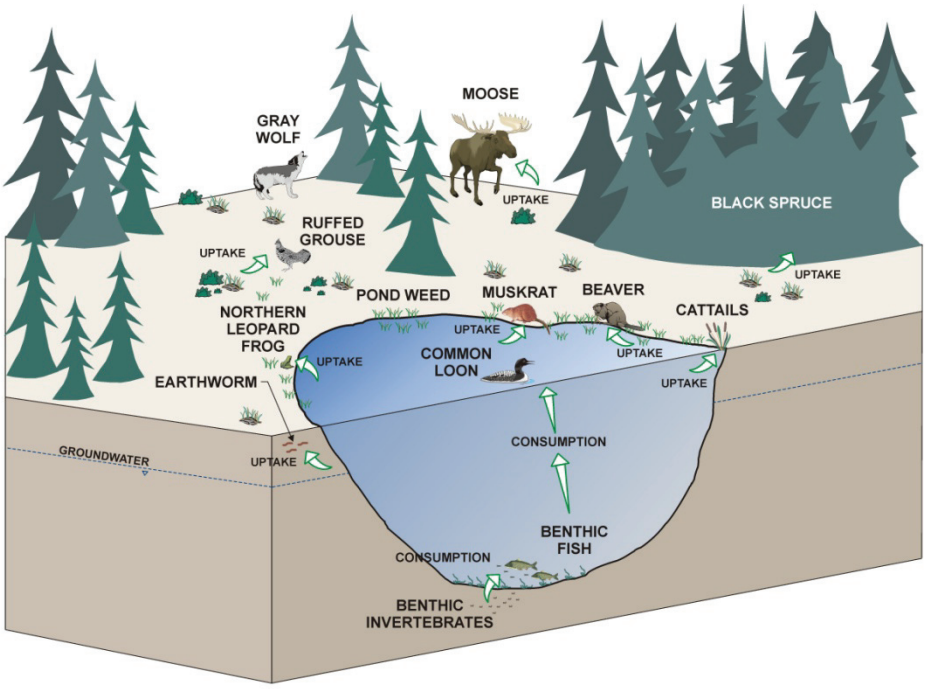


Figure 5.6: Representation of conceptual model for boreal forest ecosystem

5.2.5 Integrated System Model

The postclosure safety assessment of a used fuel repository uses several complementary computer models. These are either commercially maintained codes, or codes maintained by NWMO under a software quality assurance system.

The main safety assessment codes for postclosure analyses are the following:
- SYVAC3-CC4 – NWMO reference integrated system model
- FRAC3DVS – 3D groundwater flow and transport model
- TOUGH2 – 3D two-phase gas & water flow model
- AMBER – compartment model.

The main software development in 2008 was the addition of states to the SYVAC3-CC4 system model so that it could evaluate the effect of time changes in geosphere and biosphere conditions, such as would occur during a glacial cycle.

5.3 CASE STUDIES

The objective of safety case studies is to provide illustrative examples of repository safety under various conditions or assumptions, and to test or demonstrate our safety assessment approach.

Three major safety assessment case studies have been considered within the Canadian program: the Environmental Impact Assessment (EIS) study (AECL 1994); the Second Case Study (SCS) (Goodwin et al. 1996); and the Third Case Study (TCS) (Gierszewski et al. 2004b). These case studies provide an opportunity to assess and illustrate the safety implications of the deep geological repository concept in the Canadian Shield. Each of the above studies considered a different combination of engineering design and site characteristics.

Our reference time frame for the safety assessment of deep repositories is one million years, roughly equivalent to the time scale for the radioactivity in used fuel to decrease to that due to its natural uranium content. Over the past one million years, the most significant natural event across Canada has been repeated glaciation cycles, which have occurred approximately every 100,000 years. It is possible that current greenhouse gas levels would delay the onset of the next glaciation, but in the long run it is prudent to assume that the glacial cycles will resume because they are driven by long-term variation in solar insolation due to earth's orbital variations.

During past glacial cycles, much of Canada has been covered by kilometre-thick ice sheets. Because these glacial cycles represent such a large potential perturbation to a site, the Canadian used fuel disposal program has been examining the implications of glaciation for many years (see, for example, Section 4.3 for recent work in the Geoscience program). The general conclusion is that an appropriately sited and sufficiently deep repository can provide containment and isolation of the used fuel during glaciation.

In the Canadian case studies completed so far, the effects of glaciation on the safety case have been qualitatively but not been quantitatively evaluated in terms of potential contaminant release to the environment. Consequently, the NWMO is presently evaluating a “Glaciation Scenario” within the context of the hypothetical Third Case Study site on the Canadian Shield. The purpose of this case study is to quantitatively assess the long-term dose implications of glacial cycles for a deep geological repository, and to understand the key factors involved.

In 2007 and 2008, various aspects of the Glaciation Scenario were explored and work was completed on developing the tools and models needed to carry out a safety assessment for a Glaciation Scenario. Preliminary results were reported in two conference papers (Garisto et al. 2008c, Lum and Garisto 2008). A brief summary of these results is provided below.

Transient groundwater flow modelling and radionuclide transport calculations for a simplified glaciation cycle were carried out using FRAC3DVS (Garisto et al. 2008c). For this preliminary work, only I-129 was modelled, released from the repository from assumed defective containers. I-129 is expected to be the major dose contributor because of its relatively high mobility and long half-life, consistent with previous Canadian safety assessments.

The calculated I-129 mass fluxes to the local lake (which is the water source assumed to be used by people) are compared in Figure 5.7 to those for similar calculations performed in a previous case study, the Horizontal Borehole Concept (HBC) study (Garisto et al. 2005). In the HBC study, a temperate climate existed throughout the entire simulation period. Figure 5.7 shows a similar overall release to the lake, but spikes of I-129 are released into the biosphere at transitions between glacial stages in the Glaciation Scenario. These spikes are partially caused by pressurization or depressurization of the flow system due to the advance or retreat of the ice sheet over the site. They are also partially caused by the instantaneous changes in numerical boundary conditions and/or geosphere properties at transitions between glacial states and are an artefact of the modelling approach. In the future, the modelling approach will be changed to reduce these artefacts.

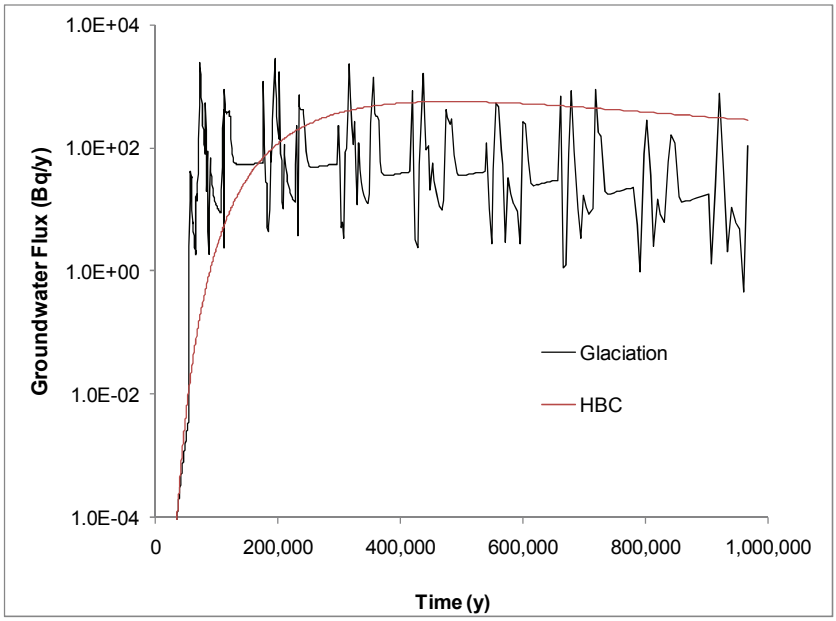


Figure 5.7: Preliminary results for I-129 flow to the lake for a climate change scenario (glaciation) and for a constant temperate climate scenario (HBC)

Potential dose rates to people were calculated using the AMBER compartmental model (Lum and Garisto 2008). These depend in part on the radionuclide flux to the biosphere as shown in Figure 5.7, but also on the habits of people in the different climate periods as well as the amount of water flowing through the surface environment. For the Glaciation Scenario, two groups are considered: a self-sufficient farmer during the temperate climate state and a hunter-gatherer during the permafrost climate state. (Both groups use the lake as their source of water.) Humans are not present when ice covers the repository site.

In Table 5.3, the calculated dose rates for the Glaciation Scenario are compared to two cases from the HBC temperate-climate case study - HBC-lake and HBC-well - in which the lake or well is the source of water for the self-sufficient farmer group. The peak dose rates from the Glaciation Scenario are similar to those for the HBC-lake case but much less than those for the HBC-well case. In all cases the peak dose rates are well below the ICRP-81 recommended dose constraint of 3×10^{-4} Sv/y. These preliminary results suggest that assuming a constant

temperate climate and a self-sufficient farmer with a well-water supply can provide a bounding estimate of the potential dose impacts of glaciation on a site.

Table 5.3: Comparison of I-129 Peak Dose Rates (preliminary results)

Case Study	Water source	Peak Dose Rate (Sv/y)	Time of Peak (years)
Glaciation Scenario	Lake	$7x10^{-10}$	200,000
HBC (Temperate climate)	Lake	$9x10^{-10}$	500,000
HBC (Temperate climate)	Well	$1x10^{-7}$	500,000

During 2008, work focussed on three main aspects towards providing a more definitive conclusion:

- Definition of a reference glaciation cycle consistent with the glaciation cycle derived by Peltier (2006), which is representative of the evolution of the Laurentide Ice Sheet over the previous 120,000 years.
- Refinement of the glaciation model reference case for groundwater and transport modelling. For example, the model presently includes an estimate for 1-D hydromechanical effects under the icesheet.
- Improvement in the FRAC3DVS and SYVAC3-CC4 models to simulate 1 Ma of glacial cycling. FRAC3DVS 3-D groundwater flow and transport runs can take up to 3 months for a one million year simulation.

The Glaciation Scenario case study will be completed in 2009.

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APPENDIX A: LIST OF TECHNICAL REPORTS, PAPERS AND CONTRACTORS

A.1 NWMO Technical Reports

K. Birch, M. Ben Belfadhel, J. Freire-Canosa, F. Garisto, P. Gierszewski, M. Hobbs, T. Kempe, G. Kwong, T. Lam, P. Lum, P. Maak, S. Russell and A. Vorauer. 2008. Technical research and development program for long-term management of Canada's used nuclear fuel – annual report 2007. Nuclear Waste Management Organization Report NWMO TR-2008-01. Toronto, Canada.

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A.4 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

4DM Inc.
Dr. T. Al, University of New Brunswick
AMEC-NSS
Dr. G. Atkinson, Carlton University/ University of Western Ontario
Atomic Energy of Canada Ltd.
Dr. J. Blatz, University of Manitoba
Candesco Corporation
N. Chandler
ECOMatters Inc.
Engineering Simulations Inc.
Enviros Consulting Ltd.
Dr. S. Frape, University of Waterloo
FSS Canada Inc.
Gascoyne GeoProjects Inc.
Golder Associates
HydroGeoLogic Inc.
Dr. B. Ikeda, University of Ontario Institute of Technology
Integrity Corrosion Consulting Ltd.
Intera Engineering Ltd.
David P. Jackson & Associates Ltd.
Dr. Klaus Jacob
Kinectrics Inc.
Dr. B. Kjartanson, Lakehead University
Dr. Shutian Ma
Dr. K. MacQuarrie, University of New Brunswick
Dr. U. Mayer, University of British Columbia
Dr. R.C. Newman, University of Toronto
Dr. K. Novakowski, Queen's University
Dr. W. Peltier, University of Toronto
Dr. Mark Person, New Mexico Institute of Mining and Technology
Quintessa Inc.
RSRead Consulting Inc.
Dr. Leonardo Seeber
Dr. P. Selvadurai, McGill University
SENES Consultants Ltd.
Serco Group PLC

Dr. D. Shoesmith, University of Western Ontario
Dr. G. Siemens, Royal Military College of Canada
G.R. Simmons & Associates Consulting Services Ltd.
John Sims and Associates
Dr. E. Sudicky, University of Waterloo
Dr. J. Sykes, University of Waterloo
Dr. R. Therrien, Université Laval
U.S. Geological Survey
Dr. Patrick Wu

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2008

ABSTRACT

Title: **Technical Research and Development Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2007**
Report No.: **NWMO TR-2008-01**
Author(s): K. Birch, M. Ben Belfadhel, J. Freire-Canosa, F. Garisto, P. Gierszewski, M. Hobbs, T. Kempe, G. Kwong, T. Lam, P. Lum, P. Maak, S. Russell and A. Vorauer
Company: Nuclear Waste Management Organization
Date: March 2008

Abstract
This report is a summary of progress in 2007 for the technical research and development program for long-term management of Canada's used nuclear fuel.

Significant achievements in 2007 include:

- Co-operation agreements were signed with Posiva (Finland), SKB (Sweden), Nagra (Switzerland) and Andra (France). These agreements will facilitate the exchange of information and participation in joint research projects.
- Canada participated in several projects at the SKB Äspö Hard Rock Laboratory in Sweden, including the Colloid Dipole Experiment, the LASGIT Gas Injection Test, the Engineered Barrier System Modelling Task Force, the Groundwater Modelling Task Force, the Long-term Test and Canister Retrieval Tests, the ROSE (rock-shear) test design, and the BACLO (backfill) project. NWMO also hosted the Äspö Modelling Task Force 7A Meeting #23 in Toronto.
- An annual technical research and development program update was held with the Canadian Nuclear Safety Commission.
- A Workshop on Used-Fuel Container Corrosion was held to discuss the current state of knowledge on corrosion of copper and steel used-fuel containers in both crystalline rock and sedimentary rock repository environments.
- A conceptual model for corrosion of a carbon steel used fuel container in a deep geological repository in sedimentary rock was developed to account for various corrosion processes that might affect the container in the repository environment.
- The potential impacts of microbial activity and salinity on the design of repository sealing system components were studied, with an emphasis on the bentonite buffer which would surround the used-fuel containers. The experimental results suggest that in a low-salinity repository environment, a bentonite dry density of 1.6 g/cm^3 and the associated high swelling pressure would be required to suppress microbial activity in bentonite.
- The 5th Annual NWMO Geoscience Seminar was held to discuss the state-of-knowledge in site characterization tools and methods, geoscientific experiments, performance assessment, flow system evolution and geosphere stability.
- The development of laboratory technique and protocols for the characterization of sedimentary rocks continued with investigating the feasibility of the ultracentrifugation method for pore water extraction and comparing the standard through-diffusion and an x-ray radiography technique for the determination of diffusive properties of rocks.

- The University of Toronto Glacial System Model was further applied to explore the time-dependent nature of surface boundary conditions on a deep geological repository.
- A seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield has been ongoing since 1982. An updated report was completed in 2007 regarding the recent advances in understanding the geology of the Canadian Shield.
- A 3-dimensional seismic monitoring program at the Sudbury Neutrino Observatory was initiated to study the influence of near-surface site effects and the potential effects of seismic response due to the free surface in cavities and tunnel. An important conclusion was that underground motions appear to be lower than those at the surface, consistent with previous qualitative observations in underground facilities.
- A review of used fuel and uranium dioxide dissolution studies in Canada and internationally was completed. The results support the view that the dissolution rate of the used fuel in a deep geological repository will be very slow.
- Samples of various fish, plants and wild biota from the Canadian Shield area were analyzed, using a new analytical technique, in order to improve our understanding of iodine transfer in the biosphere.
- Numerical methods development included the implementation of a number of improvements to the code FRAC3DVS-OPG. A quality assurance framework for maintaining and modifying the code was also developed.
- A Safety Assessment Modelling Workshop was held to discuss progress on modelling the various stages of the glaciation cycle and the potential impact of glaciation on a deep geological repository.
- In 2007, results from scoping analyses of a repository under glacial conditions were completed using the safety assessment CC4 system model, the FRAC3DVS detailed transport model and an AMBER biosphere model. These scoping analyses have illustrated key factors and possible numerical approaches for further evaluation in 2008.

ABSTRACT

Title: **No-Effect Concentrations for Screening Assessment of Radiological Impacts on Non-Human Biota**
Report No.: **NWMO TR-2008-02**
Author(s): Nava C. Garisto, Farrah Cooper and Stacey L. Fernandes
Company: SENES Consultants Limited
Date: April 2008

Abstract
This study presents and implements a screening methodology for assessing the potential post-closure radiological impact of a deep geological repository for used nuclear fuel on non-human biota. This screening methodology is designed for hypothetical sites representative of selected Canadian conditions under both present and potential future climate conditions. The screening is carried out by comparing estimated radionuclide concentrations to derived "No Effect Concentrations" (NECs). The NECs are screening or threshold criteria; the conservative nature of the assumptions used to derive the NECs ensures that as long as the NECs are not exceeded, there is confidence that, despite uncertainty in modelled environmental concentrations, there will be no significant ecological effect on non-human biota. In the event NECs are exceeded in screening calculations, a site-specific Ecological Risk Assessment (ERA) would be required to determine whether this is due to conservatism in the assumptions, lack of sufficient data or potential real impact.

NECs are derived in this study for groundwater, soil, surface water and sediment in three ecosystems that represent a range of Canadian conditions: southern Canadian deciduous forest, boreal Canadian Shield forest, and tundra (a potential far-future climate condition during glaciation).

Several indicator species are evaluated for each ecosystem, representing a range of different trophic levels within the ecosystem. The NEC corresponding to the most limiting biota for each radionuclide in a particular environmental medium is used as a concentration screening level. A sum-of-fractions rule has to be used to ensure that the total dose over radionuclides and media does not exceed the estimated no-effect dose-rate values (i.e., radioecological dose benchmarks for population-level effects on biota; these values are compiled from literature).

These NECs were compared to post-closure environmental concentrations estimated in major Canadian post-closure assessments of the geological disposal of used fuel, including the Third Case Study, the Second Case Study and the Environmental Impact Statement study. The results indicate that there would be no significant radioecological impact on non-human biota for these case studies.

ABSTRACT

Title: **DECOVALEX THMC TASK E – Implications of Glaciation and Coupled Thermohydromechanical Processes on Shield Flow System Evolution and Performance Assessment**
Report No.: **NWMO TR-2008-03**
Author(s): T. Chan and F.W. Stanchell
Company: Atomic Energy of Canada Limited
Date: August 2008

Abstract
A Deep Geological Repository (DGR) situated on the Canadian Shield will be subject to long-term climate change that will markedly alter surface conditions as a result of glaciation and permafrost penetration. Task E of DECOVALEX THMC[1] is a systematic numerical case study of the subsurface THM processes and mechanisms arising from long-term climate change. The case study focuses on predicting the magnitudes and rates of change in groundwater flow and state of stress caused by time-varying glacial boundary conditions acting on a 1.6-km deep, subregional scale (≈100 km^2), fractured Shield flow system adapted from Sykes et al. (2004) and includes a simplified version of the stochastic Fracture-zone Network Model (FNM) of Srivastava (2002). Transient, 2- and 3-dimensional (2D and 3D) MOTIF finite-element, coupled THM, subsurface simulations were completed. Depth-dependent fluid salinity and temperature-dependent fluid density and viscosity have been included, as well as initial and transient thermal, hydraulic and mechanical boundary conditions developed from two 120,000-year Laurentide glaciation scenario realizations of the University of Toronto's Glacial Systems Model (GSM) (Peltier's 2003). The GSM model provides varying magnitudes and rates of change in basal normal stress, temperature, meltwater fluxes and permafrost evolution.

Selected key findings of Task E coupled THM subsurface modelling include: i) for this particular conceptual model, the flow domain appears to have little memory of previous glacial cycles, with respect to carryover of significant thermal and hydraulic effects; ii) the increase of hydraulic head under ice loading, primarily caused by consolidation effects, is not equal to the total stress imposed by the glacier on the bedrock, but rather is about 1/3 of the glacial basal normal stress, in part due to the ratio between the compressibilities of the rock and the water; iii) the incremental head values resulting from ice loading and HM coupling are relatively uniform throughout the modelled subregion both horizontally and vertically, in contrast to what would occur if one used a hydraulic head boundary condition equivalent to the ice-sheet thickness in an uncoupled flow model; iv) head values in fracture zones (FZs) differ from those in the adjacent rock mass (RM) by a few metres; v) sensitivity analyses showed that a combination of a temperate glacier, very low permeability rock (~10^{-20} m^2) and limited FZ connectivity is necessary for residual anomalous hydraulic heads to persist at depth for thousands of years following deglaciation; vi) during the glacial cycle, Darcy fluxes (velocities) in the FZs and highly permeable RM near surface are on the order of 10^{-2} to 10^{-1} m/a and range between 10^{-7} to 10^{-5} m/a in the RM below 350 m; vii) through using 2D simulations and thereby removing most of the FZ interconnectivity, groundwater velocities in the FZs were reduced by a factor of 100; viii) conservative particle-tracking analysis indicated that 72% of glacial meltwater particles did not penetrate more than 70m below surface and only 6% penetrated to 500m or further[2] below

[1] An International Project for DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation involving coupled Thermal-Hydraulic-Mechanical-Chemical processes, 2004-2007.

[2] The meltwater penetration depth might have been overestimated because simplification of the original FNM has led to higher predicted groundwater velocities in FZs.

surface; ix) meltwater penetration depths are slightly enhanced by thermal effects, slightly diminished by density effects from depth dependent salinity, slightly enhanced by simulating a smooth glacial topography, hardly influenced by the glacial scenario (within the two scenarios simulated), but severely underestimated by using a 2D model that truncates most of the FZ connectivity; x) during glacial advance/retreat, principal effective stresses are re-oriented, factor of safety is slightly enhanced in the RM and reduced in the FZs.

A limited 2D numerical study was conducted on subregional Shield groundwater flow dynamics under permafrost conditions. A time-invariant, uniform 350-m thick layer of low-permeability ($\sim 10^{-19}$ m^2) rock was used to model the permafrost. Results of the coupled HM simulations with salinity are summarized with a focus on comparing Darcy flux trends with depth with and without permafrost.

DECOVALEX THMC Task E has contributed to an improved understanding of the impact of glaciation on the geosphere including deep flow system behaviour and geomechanical stability. In particular, the application of coupled thermal-hydraulic-mechanical modelling to study glaciation impacts has been demonstrated and the resulting geosphere responses relevant to performance assessment for a DGR have been highlighted.

ABSTRACT

Title: **PRELIMINARY RESULTS OF ONE-DIMENSIONAL CONSOLIDATION TESTING ON BENTONITE CLAY-BASED SEALING COMPONENTS SUBJECTED TO TWO PORE-FLUID CHEMISTRY CONDITIONS**
Report No.: **NWMO TR-2008-04**
Author(s): P. Baumgartner[1], D. Priyanto[1], J.R. Baldwin[2], J.A. Blatz[2], B.H. Kjartanson[3] and H. Batenipour[3]
Company: [1]Atomic Energy of Canada Limited, [2]University of Manitoba and [3]Lakehead University
Date: March 2008

Abstract
One-dimensional consolidation tests are performed to provide preliminary information on the time-dependent deformation properties of saturated highly compacted bentonite (HCB), light backfill (LBF) and dense backfill (DBF), three potential sealing-system components of the Emplacement-Room Sealing System. Testing includes an examination of the influence of pore-fluid salinity on the consolidation behaviour to assess the importance of groundwater chemistry on system performance.

This report provides the details of the tests including their results. The combined results of all three sealing-system components are compared on the common basis of the effective montmorillonite dry density (EMDD) and also compared to previously established swelling-pressure measurements. The resultant void ratios, dry densities and EMDDs tend to be related to the swelling pressures associated with distilled water and highly saline pore fluids. Fitted expressions for the one-dimensional constrained moduli (stiffness) are also presented for use in modelling. The appendices in this report present the procedures used in all of the testing, the detailed measurements taken during the tests, comparisons of the test results in light of the initial conditions and the modifications to the material-property calculations when saline solutions replace distilled water as the pore fluid.

ABSTRACT

Title: **Triaxial Characterization of Light and Dense Backfill to Determine Properties for use in Numerical Modeling**
Report No.: **NWMO TR-2008-05**
Author(s): J.A. Blatz[1] G. Siemens[2] and A. Man[3]
Company: [1]University of Manitoba, [2]Royal Military College of Canada
[3]Atomic Energy of Canada Limited
Date: March 2008

Abstract
This report presents the results of triaxial testing directed at characterization of mechanical properties of light and dense backfill materials that contain freshwater as the pore fluid. The results of the triaxial testing program provide the isotropic consolidation and stress-strain properties of light backfill (LBF) and dense backfill (DBF) materials under saturated conditions. These properties are required parameters for simulating the behaviour of these materials during numerical modeling activities.

In the in-room emplacement geometry for used nuclear fuel, light and dense backfill materials will be required as barrier materials that will surround spent fuel containers and will support them in the short term during construction and in the long term following repository closure. In the in-floor geometry for container emplacement the backfill materials will be used to fill the access tunnels immediately above the emplacement boreholes, preventing upwards swelling of the buffer materials that surround them. These barrier materials will also be expected to conduct heat away from the waste containers to the surrounding rock and limit contaminant transport by groundwater. As a result of these requirements, establishing the mechanical performance of LBF and DBF under varying moisture, temperature, chemical and pressure conditions are critical to understanding their intended performance in underground disposal concepts. The test results presented in this report is part of the process of characterizing the mechanical behaviour of LBF and DBF under saturated conditions with freshwater as the pore fluid.

The testing program includes standard triaxial testing at three confining pressures (400 kPa, 800 kPa and 1,200 kPa) to establish the consolidation characteristics of the backfill materials under isotropic loading and shear characteristics under shear loading. The tests were conducted under both drained and undrained conditions for both materials. The results allow interpretation of both strength and deformation or stiffness parameters (Bulk Modulus and Young's modulus) providing materials parameters for use in numerical models. The work also included development of laboratory preparation procedures and standards for testing these two materials.

The results of the testing program indicate that the Bulk Modulus for the LBF is 2.8 MPa and the average Young's Modulus for the material is 155.9 MPa. The critical state strength envelope for the LBF has a slope of M = 0.47, with a corresponding critical state friction angle of 13.5°. The strength of this material is similar to that of natural glacial lake clays.

The DBF material was found to be both stiffer and stronger than the LBF. The Bulk Modulus for the DBF is 10.7 MPa and the average Young's Modulus for the material is 261.7 MPa. The critical state strength envelope for the LBF has a slope of M = 1.10, with a corresponding critical state friction angle of 28°.

Additional testing (i.e. triaxial consolidation testing) is required to confirm the above Bulk Modulus values and subsequently determine a Poisson's Ratio for the materials. Greater confidence is given to the Young's Modulus values presented in this report.

As part of the on-going series of tests associated with this work the tests described in this report are being repeated using saline pore fluid. This is being done to provide comparative values for materials exposed to groundwater conditions that might be encountered under the geochemical conditions present in Ordovician sedimentary rocks.

ABSTRACT

Title: **The Effects of Initial Conditions and Liquid Composition on the One-Dimensional Consolidation Behaviour of Clay-Based Sealing Materials**
Report No.: **NWMO TR-2008-06**
Author(s): D. G. Priyanto[1], J. A. Blatz[2], G. A. Siemens[3], R. Offman[2], J. S. Boyle[3], and D. A. Dixon[1]
Company: [1]Atomic Energy of Canada Limited;
[2]University of Manitoba;
[3]Royal Military College of Canada
Date: March 2008

Abstract
Groundwaters at proposed repository depths of 500 to 1000 m can contain significant quantities of soluble salts (Gascoyne et al. 1987; Mazurek 2004). These salts have the potential to affect the hydraulic-mechanical behaviour of clay-based sealing materials installed in a Deep Geological Repository (DGR) of the type presented by Russell and Simmons (2003) and Maak and Simmons (2005). As a result of the influence of liquid salinity on material behaviour, one of the design decisions for the engineering of a sealing system is whether to prepare the sealing materials with fresh or saline liquid (Baumgartner et al. 2008) and to determine if this will affect the performance of the barrier materials.

The results of one-dimensional (1D) consolidation tests conducted in 2007 on three clay-based sealing materials including: Highly Compacted Bentonite (HCB); Dense Backfill (DBF); and Light Backfill (LBF) are presented and discussed. Testing was conducted at three different laboratories: Atomic Energy of Canada Limited (AECL)'s geotechnical laboratory at the Underground Research Laboratory (URL) (HCB); the University of Manitoba (U of M) (DBF); and the Royal Military College of Canada (RMC) (LBF).

The 1D consolidation tests are used to examine the effects of: boundary conditions and applied load during initial saturation; and high pore liquid salinities (up to 250 g/L $CaCl_2$) used in specimen preparation and as a reservoir liquid. Parameters to define the mechanical behaviour (i.e., Compression Index (C_c) and Swelling Index (C_s)) of the HCB, DBF, and LBF have been determined from the results of these tests. The values of these parameters were found to decrease with an increase in concentration of calcium chloride ($CaCl_2$) solution in pore liquid. The relationship of these parameters to the pore liquid composition is suggested for use in defining the mechanical behaviour of clay-based sealing materials in THM numerical modelling.

ABSTRACT

Title: **Theory Manual for the Copper Corrosion Model for Uniform Corrosion in Sedimentary Rock CCM-UC.1.1**
Report No.: **NWMO TR-2008-07**
Author(s): Fraser King
Company: Integrity Corrosion Consulting Limited
Date: April 2008

Abstract
A mechanistically based model for the uniform corrosion of copper used fuel containers in a deep geological repository in sedimentary deposits is described. The model is termed the Copper Corrosion Model for Uniform Corrosion (CCM-UC). The mechanism accounts for all of the important processes involved in the corrosion of copper in porous media in contact with O_2-containing chloride solutions, including: interfacial electrochemical reactions, precipitation/dissolution, adsorption/desorption, redox, and mass-transport processes. These processes have been selected based on the results of an extensive experimental program with copper (Cu) materials.

These processes are expressed mathematically in the form of a series of ten coupled, one-dimensional reaction-diffusion equations, one for each of the chemical species included in the model, namely: gaseous and dissolved O_2, dissolved $CuCl_2^-$, precipitated Cu_2O, dissolved and adsorbed Cu^{2+}, precipitated $CuCl_2 \cdot 3Cu(OH)_2$, Cl^-, and dissolved and precipitated Fe(II). In addition, a heat-conduction equation is included to account for the spatial and temporal variation of temperature within the repository.

From a corrosion viewpoint, the two characteristics of typical deep sedimentary formations that distinguish them from a crystalline host rock are the higher salinity groundwater and the lower hydraulic conductivity. The higher groundwater salinity, especially the higher chloride concentration, will (i) promote uniform corrosion over localized corrosion or stress corrosion cracking, (ii) effect the speciation and stability of Cu(I) species, and (iii) inhibit microbial activity. The lower hydraulic conductivity will result in an extended unsaturated period in the deep geological repository which will have the following effects: (i) a period of no aqueous corrosion, (ii) faster diffusion of O_2 and slower diffusion of dissolved species, and (iii) restricted microbial activity.

The mathematical treatment of the various processes and their dependence on the repository design and environmental factors such as temperature, redox conditions, and the degree of saturation are described. The model incorporates an electrochemical mixed-potential model which allows the prediction of the corrosion potential and the corrosion rate. Finally, the finite-difference technique used to solve the reaction-diffusion equations is also described in some detail.

ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2007**
Report No.: **NWMO TR-2008-08**
Author(s): S. Hayek, J.A. Drysdale, V. Peci, S. Halchuk, J. Adams and P. Street
Company: Canadian Hazards Information Service, Geological Survey of Canada
Date: December 2008

Abstract
The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC) continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2007.

CHIS maintains a network of twenty-six seismograph stations to monitor low levels of background seismicity in the northern Ontario and eastern Manitoba portions of the Canadian Shield. Core stations are located at: Sioux Lookout (SOLO), Thunder Bay (TBO), Geraldton (GTO), Kapuskasing (KAPO), Eldee (EEO), and Chalk River (CRLO). These are augmented by the POLARIS and FedNor networks of temporary stations at: Musselwhite Mine (MUMO), Sutton Inlier (SILO), Otter Rapids (OTRO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Red Lake (RLKO), Experimental Lake (EPLO), Pickle Lake (PKLO), Lac-des-Iles (LDIO), Pukaskwa National Park (PNPO), Kasabonika Lake (KASO), Neskantaga (NSKO), Aroland (NANO), Moosonee (MSNO), Timmins (TIMO), and Haileybury (HSMO). The digital data from a temporary station at Victor Mine (VIMO), partially funded by the diamond mine industry, and a station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) are also used in this study.

All the stations are operated by CHIS and transmit digital data in real-time via satellite to a central acquisition hub in Ottawa. CHIS staff in Ottawa integrate the data from these stations with those of the Canadian National Seismograph Network and provide monthly reports of the seismic activity in northern Ontario. This report summarizes seismic monitoring results for the year 2007.

During this twelve-month period 68 earthquakes were located. Their magnitude (m_N) ranged from 1.1 to 3.0. The largest events included a m_N 3.0 and a m_N 2.8 in James Bay, and two m_N 2.9s and a m_N 2.8 in the Cochrane-Kapuskasing region of Ontario. The most westerly event in the area being studied was a m_N 1.4 event located just west of Kenora, ON. The 68 events located in 2007 compares with 83 events in 2006, 103 events in 2005, 79 events in 2004, and 45 located events in 2003 and 2002. The general increase in located events is a reflection of the lower location threshold since the progressive addition of FedNor stations from 2003 to 2005.

ABSTRACT

Title: **Preliminary Microbial Analysis of Limestone and Shale Rock Samples**
Report No.: **NWMO TR-2008-09**
Author(s): S. Stroes-Gascoyne and C.J. Hamon
Company: Atomic Energy of Canada Limited
Date: July 2008

Abstract
Samples of Ordovician sediments (Queenston shale and Cobourg limestone) were obtained from Ontario Power Generation Inc. for preliminary microbial characterization in support of the Nuclear Waste Management Organization's technical research and development program. The samples were analyzed with culture techniques using both dilute growth media and media based on the saline porewater compositions in these sediments, to account for the possible presence of indigenous halotolerant or halophilic microorganisms. The samples were also examined for phospholipid fatty acids (PLFA), neutral lipid fatty acids (NLFA) and glyco-lipids (diglyceride fatty acids, GLFA), three biomarkers from which the presence of viable (PLFA) and dead cells (NLFA and GLFA) can be derived. Results suggested strongly that in accordance with expectations, based on measured water content (0%) and very low water activity (<0.2), no viable (halophilic or other) bacteria were present in the limestone rock but that some contamination of the limestone sample with common (facultative) aerobic cells occurred, likely during drilling or sample handling. The results for the shale sample indicated the presence of viable microorganisms, based on PLFA measurements. However, because of the very low water activity in this shale sample (0.34) (1% water content), this result may not be valid, because it is currently somewhat uncertain whether the PLFA, NLFA and GLFA biomarkers are reliable in a very low water activity environment. If the method is valid, the results for the shale sample would indicate a biologically mostly inactive environment because of the presence of relatively large quantities of dead cells, compared to viable (live) cells. Bacterial species indicated in the aerobic and anaerobic shale enrichment cultures were common non-halophilic, mostly facultative anaerobic sporeformers (including a pathogen). Because of the presence of PLFA, it cannot be ruled out that some of the microorganisms could be indigenous to the shale and survived for a long time in situ as spores in the shale formation. However, this is expected to be very unlikely because of the high similarity with common aerobic surface bacteria (including a human pathogen).

ABSTRACT

Title: **Preliminary Assessment of Potential Technical Implications of Reactor Refurbishment and New Nuclear Build on Adaptive Phased Management**
Report No.: **NWMO TR-2008-10**
Author(s): S. Russell
Company: Nuclear Waste Management Organization
Date: December 2008

Abstract
Since the Nuclear Waste Management Organization (NWMO) submitted its Final Study in 2005, there have been a number of planned and proposed nuclear refurbishment and new build initiatives which could extend the projected end of nuclear reactor operation in Canada from about 2034 to about 2085 or beyond.

The important technical features of these recent nuclear initiatives include:

- The amount of used nuclear fuel produced in Canada;
- The type of used nuclear fuel produced in Canada; and
- The duration of operation of long-term management facilities in Canada.

The NWMO conducted a preliminary assessment of the potential technical implications of these nuclear initiatives on Adaptive Phased Management and found the following:

1. The amount of used nuclear fuel will determine the design size of the deep geological repository and the requirements for a potentially suitable site. As of January 1, 2008, Canada had about 2 million used CANDU fuel bundles for long-term management and conceptual designs have been developed for a used fuel inventory ranging from 3.6 million to 10 million used fuel bundles. A single deep geological repository could be designed to accommodate a wide range of inventory of used nuclear fuel from existing reactors as well as from proposed new-build reactors.

2. The type of nuclear reactors in Canada will determine the type of used nuclear fuel for long-term management which will impact:
    i. the physical dimensions of the waste form, for example, small fuel bundles from CANDU reactors and large fuel assemblies from pressurized water reactors or boiling water reactors; and
    ii. the heat output from used fuel due to the concentration of fission products. Used fuel enriched with uranium-235 will be hotter and thus a smaller amount of enriched uranium fuel can be placed in a container and more repository area is required per container compared to non-enriched fuel.

3. The duration of operation of used fuel transportation, used fuel re-packaging, placement in a deep geological repository and monitoring would be extended by many decades beyond the 30-year operating period associated with a used fuel inventory of 3.6 million bundles. Essentially, each year of continued nuclear reactor operation in Canada would extend the duration of operation of long-term management facilities by about another year.

ABSTRACT

Title: **The Effect of Intermediate Dry Densities (1.1-1.5 g/cm^3) and Intermediate Porewater Salinities (60-90 g NaCl/L) on the Culturability of Heterotrophic Aerobic Bacteria in Compacted 100% Bentonite**
Report No.: **NWMO TR-2008-11**
Author(s): S. Stroes-Gascoyne and C.J. Hamon
Company: Atomic Energy of Canada Limited
Date: September 2008

Abstract
Highly compacted bentonite-based sealing systems are being developed for potential use in many nuclear fuel waste repository concepts. Due to the inherent physical characteristics of these materials such as low water activity, small pores and high swelling pressure, an important role of highly compacted bentonite is the reduction of significant microbial activity near the used fuel containers in a deep geological repository (DGR), which would reduce or eliminate the possibility of microbially influenced corrosion (MIC). Previous work determined that a dry density of $\geq$1.6 g/cm^3 or a porewater salinity of > 100 g NaCl/L would keep microbial culturability at or below background levels in highly compacted bentonite buffer (i.e., $\leq$ 2 x 10^2 Colony-Forming Units/g). In order to fill in some of the gaps left by the previous study, this report examines the effects of intermediate NaCl porewater concentrations (i.e., 60, 70, 80 and 90 g/L) on the culturability of microbes in compacted bentonite at target dry densities of 1.2, 1.4, 1.6 and 1.8 g/cm3. In addition, the effects of a porewater salinity of 0 and 100 g NaCl/L on microbes in compacted bentonite at intermediate dry densities (i.e., target dry densities of 1.1, 1.2, 1.4 and 1.5 g/cm3) were also examined. The additional data suggest that the previous requirements for bentonite dry density or porewater salinity to keep microbial culturability at or below background levels in the highly compacted bentonite buffer (i.e., $\geq$ 1.6 g/cm^3 or > 100 g NaCl/L) have been confirmed and that those requirements could likely be lowered to $\geq$ 1.4 g/cm^3 or > 50 g NaCl/L. However, in order to fully confirm that a dry density of $\geq$ 1.4 g/cm^3 and <1.6g/cm^3 is sufficient to suppress microbial activity and render MIC insignificant, it is recommended that actual pore sizes be measured in Wyoming MX-80 bentonite plugs of this range of dry densities. It is also recommended that porewater salinity studies with $CaCl_2$ be performed to ensure that in saline Ca-dominated groundwaters the salinity effects on microbes indigenous in Wyoming MX-80 bentonite would be the same as those determined with NaCl solutions in this study. It is further emphasized that the conclusions are valid for microbes indigenous in Wyoming MX-80 bentonite, but are not necessarily directly applicable to other brands of bentonite without further study.

ABSTRACT

Title: **The Effect of High Chloride Concentration on Stress Corrosion Cracking Behaviour of Copper**
Report No.: **NWMO TR-2008-12**
Author(s): B.M. Ikeda[1] and C.D. Litke[2]
Company: 1. University of Ontario Institute of Technology
2. Atomic Energy of Canada Limited
Date: December 2008

Abstract
In this study, the effect of high concentrations of chloride on the stress corrosion cracking (SCC) behaviour of oxygen free phosphorous doped (OFP) copper was investigated in nitrite, ammonia, and acetate environments at room temperature. All experiments in the study were constant extension rate tests using a compact tension specimen under a galvanically applied current of 1 $\mu A \cdot cm^{-2}$. The corrosion potential was measured during each experiment. The experimental findings are summarized as follow:

- In a 0.1 $mol \cdot L^{-1}$ nitrite solution, copper could be subjected to extensive SCC in the presence of ≤ 0.01 $mol \cdot L^{-1}$ (i.e., ~0.6 $g \cdot L^{-1}$) NaCl. However, the addition of 0.1 $mol \cdot L^{-1}$ (~6 $g \cdot L^{-1}$) and 5.5 $mol \cdot L^{-1}$ (i.e., ~320 $g \cdot L^{-1}$) NaCl would suppress SCC.

- In a 1 $mol \cdot L^{-1}$ ammonia solution, copper could be subjected to extensive SCC in the absence of NaCl and in the presence of 0.5 $mol \cdot L^{-1}$ (~30 $g \cdot L^{-1}$) NaCl. However, the addition of ~5.5 $mol \cdot L^{-1}$ (~320 $g \cdot L^{-1}$) NaCl would suppress SCC.

- In a 0.1 $mol \cdot L^{-1}$ acetate solution, copper could be susceptible to SCC in the presence of ≤ 0.01 $mol \cdot L^{-1}$ NaCl. However, the extent of SCC would be limited. The addition of higher concentrations of NaCl (0.1 and ~ 5.5 $mol \cdot L^{-1}$, i.e., 6 $g \cdot L^{-1}$ and 320 $g \cdot L^{-1}$) suppressed SCC and only ductile tearing was observed for the copper specimens.

The present study appears to indicate a high concentration of ~5.5 $mol \cdot L^{-1}$ (~320 $g \cdot L^{-1}$) NaCl would suppress SCC in nitrite, ammonia, and acetate solutions. The high NaCl concentration would suppress SCC by promoting uniform corrosion and disrupting oxide film formation on the crack surface. The stress corrosion factor (SCCF1), surface crack extension rate (SCER), and visual examination of the copper specimens suggested ductile behaviour in high chloride concentrations.

ABSTRACT

Title: **Modelling the Compliance of Swelling Clay Sealing Systems: In-Floor Borehole and Horizontal Borehole Numerical Simulations**
Report No.: **NWMO TR-2008-13**
Author(s): N. A. Chandler
Company: Independent Engineering Consultant
Date: November 2008

Abstract
Compliance modelling can provide insight into density changes of swelling clay materials upon saturation. For example, the higher the dry density of bentonite after saturation at the surface of a used-fuel container, the lower is the potential for microbially-influenced corrosion of the container. This report describes a numerical analysis that considers the relative compliance of the swelling and non-swelling clay materials upon full saturation. The Fast Lagrangian Analysis of Continua (FLAC) analysis software code was used, and non-linear elastic properties were input into the model. The non-linear properties were based on the relationship between mean stress, or swelling pressure, and Effective Montmorillonite Dry Density (EMDD). Different density versus mean stress relationships were used for different pore water salinities and also to represent different mean stress versus volume strain paths during swelling expansion (unloading) and compression (loading).

Two different container placement options for a deep geological repository for used nuclear fuel were simulated: a horizontal borehole option, and a vertical in-floor borehole option. In both options, highly compacted bentonite (HCB) was placed adjacent to a material comprised of bentonite pellets or granules. Upon saturation, the expansion of the HCB resulted in a reduction of its dry density concurrent with a compression of the adjacent bentonite pellet materials. Compliance modelling provides a tool for assessing the required as-placed densities of both the HCB and bentonite pellets in order to achieve specific targets for long-term dry densities. Results are presented relative to a minimum dry density of 1.4 Mg/m^3 for the bentonite adjacent to the used-fuel container. 1.4 Mg/m^3 represents the dry density of bentonite above which research indicates microbe culturability to be at or below background levels.

ABSTRACT

Title: **Developing a Reasoned Argument that No Large-Scale Fracturing or Faulting Will Be Induced in the Host Rock by a Deep Geological Repository**
Report No.: **NWMO TR-2008-14**
Author(s): Rodney S. Read
Company: RSRead Consulting Inc.
Date: December 2008

Abstract
This report provides a Reasoned Argument that no large-scale fracturing or faulting will be induced in the host rock by a deep geological repository (DGR). The report considers four DGR designs in three possible host rocks, including crystalline and sedimentary rock types. The Reasoned Argument draws information from results of previously conducted thermal-mechanical analyses and simple scoping calculations using closed-form solutions, along with evidence from experiments conducted in Canada and elsewhere. The report concludes that large-scale fracturing in the far-field is implausible given the expected in situ stress conditions in relation to rock strength. Near-field damage development and fracturing are expected in many of the DGR scenarios in the different rock types, but these near-field effects are not expected to lead to large-scale fracturing that would compromise the integrity of the DGR and surrounding rock mass. The report identifies thermo-poroelastic effects as one possible driving mechanism that should be studied further, and provides other recommended analysis and characterization activities to further validate the conclusions drawn from the Reasoned Argument.

ABSTRACT

Title: **Review of Satellite, Airborne and Surface Based Geophysical Tools and Techniques for Screening Potential Nuclear Repository Candidate Sites**
Report No.: **NWMO TR-2008-15**
Author(s): Simon Emsley, George Schneider, Stephané Sol, Jeffrey Fleming and John Fairs
Company: Golder Associates
Date: December 2008

Abstract
This report presents a discussion of the available geophysical techniques that could be used in a site screening programme for a deep underground repository. The techniques considered in this report include satellite, airborne and surface based techniques, with the surface based techniques being subdivided into shallow and deep geophysical methods. The report provides guidance on the benefits that specific techniques may provide along with some constraints. Details on the accuracy and resolution of geophysical methods are provided. These are guidelines as they are dependent on many investigation specific factors, including depth of the target, geology and topography, to name a few.

The report has also reviewed some of the geophysical investigations undertaken in other countries around the world as part of their site characterisation programmes for a deep geological repository, essentially looking from the perspective of the two geological environments most closely related to the Canadian programme: sedimentary and crystalline host rocks. This review complements the sections on geophysical techniques, as it illustrates the application of these methods in a relevant context.

Canada is well advanced in geophysical exploration for hydrocarbons (sedimentary rock environments) and at the forefront in geophysical exploration for mineral deposits (crystalline rock environments). As such, the equipment and the contractors required to perform the geophysical surveys and techniques discussed in this report are commercially available in the Canadian market. Canada is also well advanced in satellite imagery and remote sensing techniques, making these methods also readily available.

Geophysical methods and remote sensing have been an integral part of the geosphere characterisation in all repository studies in both crystalline and sedimentary rock. Many satellite, surface and airborne techniques have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development, and the available technology at the time.

ABSTRACT

Title: **The Role of Rock Engineering in Developing a Deep Geological Repository in Sedimentary Rock**
Report No.: **NWMO TR-2008-16**
Author(s): Rodney S. Read
Company: RSRead Consulting Inc.
Date: December 2008

Abstract
Rock engineering will play an important role in siting, design, and construction of a deep geological repository (DGR) for nuclear fuel waste in Canada. Post-construction activities such as long-term monitoring, decommissioning, and closure will also require rock mechanics expertise. The type of host rock selected for a DGR will influence the scope of rock engineering activities and related research requirements. Considerable research has been completed on the potential for crystalline rock of the Canadian Shield as a host medium for a DGR. Less information has been compiled for the potential use of sedimentary rock as a host medium. In keeping with the selection of Adaptive Phased Management as the preferred approach for long-term management of Canada's nuclear fuel waste, this report identifies key rock engineering aspects to be considered in advancing the understanding of sedimentary rock as a host medium for a DGR.

ABSTRACT

Title: **URL EXCAVATION DESIGN, CONSTRUCTION AND PERFORMANCE**
Report No.: **NWMO TR-2008-17**
Author(s): G.W. Kuzyk and J.B. Martino
Company: Atomic Energy of Canada Limited
Date: December 2008

Abstract
Atomic Energy of Canada Limited's (AECL's) Underground Research Laboratory (URL) is a well-characterized facility constructed in the Lac du Bonnet batholith in southeastern Manitoba. Characterization commenced prior to construction, providing a sound geotechnical understanding of in situ conditions for large-scale experiments in a granitic rock mass representative of intrusive igneous rock of the Canadian Shield.

Achieving a stable underground opening requires knowledge of the geological conditions, determining the design of the ground-support system, the design and implementation of a suitable excavation method and a suitable contractual arrangement with experienced excavation, inspection and quality control personnel.

Excavation is normally performed by qualified Contractors to the quality requirements set out in the agreed upon contracts. This requires a form of contract that efficiently and cost-effectively delivers the specified excavation quality and the needed characterization information within an inherently uncertain working environment. The onus is on the owner to identify an appropriate contract format and closely monitor the progress of the work to ensure the specified requirements are met. This can best be achieved by close cooperation between the owner and the Contractor.

The preferred form of contract developed at URL for shaft sinking was a cost plus fixed fee contract format, which facilitated quality excavation in a manner that encouraged cooperation between the owner and the Contractor. Horizontal tunnelling and construction work was carried out under time and material service contracts. Integration of the Contractors' organizations facilitated close cooperation and was the key for success in these contracts. The URL was carefully designed, constructed and monitored throughout its existence. The Observational Method developed by Peck for geotechnical projects was implemented. Detailed records comprising shift inspection, construction and geotechnical reports were kept of the construction activities and the quality of the excavations. The stability of the excavations, some being subjected to high in situ rock stresses, was demonstrated and documented over more than twenty years.

This report reviews the excavation contracts in the context of the knowledge that existed at the time of procurement, the knowledge gained from the effectiveness of those contracts in achieving the desired quality of the excavations, the specification and achievement of the excavation method standard.

ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2008 Update**
Report No.: **NWMO TR-2008-18**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2008

Abstract
Since the Nuclear Waste Management Organization submitted its Final Study in 2005, there have been a number of planned and proposed nuclear refurbishment and new build initiatives which could extend the projected end of nuclear reactor operation in Canada from about 2034 to about 2085 or beyond.

The important technical features of these recent nuclear initiatives include:

- The amount of used nuclear fuel produced in Canada; and
- The type of used nuclear fuel produced in Canada;

This report summarizes the existing inventory of used CANDU nuclear fuel wastes in Canada as of June 30, 2008 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors.

As of June 30, 2008, a total of 2.0 million used CANDU fuel bundles were in storage at the reactor sites. For the existing reactor fleet, the total used fuel produced to end of life of the reactors ranges from 2.8 to 5.5 million used CANDU fuel bundles (56,000 tonnes of heavy metal (t-HM) to 110,000 t-HM), depending upon decisions taken to refurbish current reactors.

Used fuel produced by potential new-build reactors will depend on the type of reactor and number of units deployed. New-build plans are at various stages of development and the decisions about reactor technology and number of units have not yet been made. If all of the potential units where a formal licence application has already been submitted are constructed, the total additional quantity of used fuel from these reactors could be up to 2.3 million CANDU fuel bundles (37,440 t-HM), or 27,000 PWR fuel assemblies (14,550 t-HM), or 27,000 BWR fuel assemblies (3,384 t-HM).

As decisions on new nuclear build and reactor refurbishment are made by the nuclear utilities in Canada, the forecasted inventory of nuclear fuel waste will be incorporated into future updates of this report.

ABSTRACT

Title: **The Role of Dissolved Hydrogen on the Corrosion/Dissolution of Spent Nuclear Fuel**
Report No.: **NWMO TR-2008-19**
Author(s): David W. Shoesmith
Company: The University of Western Ontario
Date: November 2008

Abstract
The literature on nuclear fuel dissolution and radionuclide release studies in aqueous solutions containing dissolved hydrogen has been reviewed. These studies include investigations with spent PWR and MOX fuels, fuel specimens doped with alpha emitters to mimic “aged” fuels, SIMFUELs fabricated to simulate spent fuel properties, and unirradiated uranium dioxide pellets and powders. In all these studies, dissolved hydrogen was shown to suppress fuel corrosion and in spent fuel studies to suppress radionuclide release.

A number of mechanisms have been either demonstrated or proposed to explain these effects, all of which involve the activation of hydrogen to produce the strongly reducing $H^{\bullet}$ radical, which scavenges radiolytic oxidants and suppresses fuel oxidation and dissolution (i.e., corrosion). Both gamma and alpha radiation have been shown to produce $H^{\bullet}$ surface species. With gamma radiation this could involve the absorption of gamma energy by the solid leading to water decomposition to $OH^{\bullet}$ and $H^{\bullet}$ radicals, with the $OH^{\bullet}$ radical subsequently reacting with hydrogen to yield an additional $H^{\bullet}$. This latter radical then suppresses fuel oxidation and scavenges radiolytic oxidants. With alpha radiation, the need to neutralize oxygen vacancies generated by recoil events can initiate the same process by decomposing water. In the absence of radiation fields activation can occur on the surface of noble metal (epsilon) particles. Since these particles are galvanically-coupled to the fuel matrix they act as anodes for hydrogen oxidation (which proceeds through surface $H^{\bullet}$ species) and forces the UO_2 to adopt a low potential. Also, there is some evidence to suggest that H_2 can be activated on the UO_2 surface in the presence of hydrogen peroxide, but the process appears to be inefficient.

Depending on the radiation fields present and the number density of epsilon particles, complete suppression of fuel corrosion appears possible even for hydrogen pressures as low as 0.1 to 1 bar. Since the corrosion of steel liners within failed waste containers could produce hydrogen pressures up to 50 bar, fuel corrosion could be completely suppressed under the long-term conditions expected in sealed repositories.

ABSTRACT

Title: **The Effects of Fluid Composition on the One-Dimensional Consolidation Behaviour of Clay-Based Sealing Materials**
Report No.: **NWMO TR-2008-20**
Author(s): D. G. Priyanto[1], J. A. Blatz[2], G. A. Siemens[3], R. B. Offman[2], J. S. Powell[3], and D. A. Dixon[1]
Company: [1]Atomic Energy of Canada Limited;
[2]University of Manitoba;
[3]Royal Military College of Canada
Date: November 2008

Abstract
Groundwaters at proposed repository depths of 500 to 1000 m can contain significant quantities of soluble salts. These salts have the potential to affect the hydraulic-mechanical behaviour of clay-based sealing materials installed in a Deep Geological Repository (DGR). As a result of the potential influence of salinity on material behaviour, one of the design decisions for the engineering of a sealing system is whether to prepare the sealing materials with fresh or saline fluid and to determine if this will affect the performance of the barrier materials. One-dimensional (1D) consolidation tests can be used as a tool in characterizing the hydraulic-mechanical behaviour of clay-based sealing materials.

This report summarizes the results of the 1D consolidation tests of three clay-based sealing materials: Highly Compacted Bentonite (HCB), Dense Backfill (DBF), and Light Backfill (LBF) that have been completed to the end of 2008. The testing program includes the use of three types of fluid either as the reservoir fluid or in specimen preparation: Distilled Water (DW), $CaCl_2$ and NaCl solutions having salinity as high as 250 g/L. In order to examine the effect of the boundary condition during initial saturation on the material performance, two different boundary conditions were applied during initial saturation: constant volume (CV) or constant vertical stress (CS).

Mechanical parameters including 1D-Modulus, Compression Index (Cc), and Swelling Index (Cs) have been interpreted from the results of these tests. Cc and Cs are found to decrease with an increase in concentration of solution in pore fluid, independent of the type of salt solution (i.e., $CaCl_2$ or NaCl). This report presents the relationship of Cc and Cs to the pore fluid concentration for use in defining the mechanical behaviour of clay-based sealing materials in THM numerical modelling.

Hydraulic conductivities (k) have also been interpreted from the results of these tests. Within each individual test, k decreases with increasing density. However, when all tests are combined, this trend is not clearly apparent indicating the difficulty in making accurate determination of k from 1D consolidation tests data.

ABSTRACT

Title: **The Stress Corrosion Cracking Behaviour of Copper in Acetate Solutions**
Report No.: **NWMO TR-2008-21**
Author(s): C.D. Litke[1] and B.M. Ikeda[2]
Company: [1] Atomic Energy of Canada Limited
[2] University of Ontario Institute of Technology
Date: December 2008

Abstract
This study investigated the effect of solution concentration, aeration, applied current and extension rate on the stress corrosion cracking (SCC) behaviour of oxygen-free phosphorous-doped copper in pH 9 acetate solutions. The constant extension rate tests were performed at room temperature using a compact tension specimen under a galvanically applied current. The corrosion potential was measured during all experiments. The findings are summarized as follows:

- In a range of acetate concentrations between 0.15 mol·L^{-1} and 0.5 mol·L^{-1}, SCC was not observed on specimens exposed to an applied current of 1 µA·cm^{-2}.
- In the 0.2 mol·L^{-1} acetate concentration, neither the presence of air in the solution nor an increase in current density to 2 µA·cm^{-2} introduced SCC.
- In the 0.5 mol·L^{-1} acetate concentration, a decrease in extension rate did not produce SCC.

The stress corrosion cracking factor, surface crack extension rate, and visual examination of the copper specimens suggested predominantly ductile behaviour under the range of acetate concentrations, solution conditions, applied current densities, and extension rates studied.

ABSTRACT

Title: **Watching Brief on Reprocessing, Partitioning and Transmutation and Alternative Waste Management Technology - Annual Report 2008**
Report No.: **NWMO TR-2008-22**
Author(s): David P. Jackson and Kenneth W. Dormuth
Company: David P. Jackson & Associates Ltd.
Date: December 2008

Abstract
This is the 2008 annual report of the Nuclear Waste Management Organization's watching brief on reprocessing, partitioning and transmutation and alternative waste management technology. International developments are reviewed based on recent published documents and on the presentations at the Nuclear Energy Agency Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation held at Mito, Japan in October 2008. Technical developments on reprocessing, partitioning and transmutation in national and international research and development programs are described. In some countries, reprocessing is part of an approach to achieve sustainable nuclear energy through closed fuel cycles and fast reactors. In Canada, the current policy is a once-through nuclear fuel cycle without reprocessing.

It is concluded that although there is extensive research in reprocessing, partitioning and transmutation, its realization is still many years in the future. In particular, the findings from studies on future nuclear energy scenarios suggested that it will take about 100 years or more (i.e., beyond 2100) before closed fuel cycles with reprocessing will achieve a sustainable nuclear future with fast reactors.

Also reported are recent developments in alternative waste management technology including the Very Deep Borehole approach to long-term management of used nuclear fuel and a new approach to the deep borehole concept.

ABSTRACT

Title: **Thermal Sensitivity Analyses to Investigate the Influence of the Container Spacing and Tunnel Spacing on the Thermal Response in a Deep Geological Repository**
Report No.: **NWMO TR-2008-24**
Author(s): R. Guo
Company: Atomic Energy of Canada Limited
Date: December 2008

Abstract
This report describes the numerical modelling of a method for placing used-fuel containers in a horizontal tunnel in a deep geological repository (DGR). A series of thermal sensitivity analyses was carried out using the CODE_BRIGHT finite-element program to investigate the influence of tunnel spacing and container spacing on the development of the container-surface temperature and the tunnel-wall temperature in a conceptual repository located at a depth of 750 m in a limestone geosphere. The influence of buffer thermal conductivity on container- and tunnel-wall temperatures in a repository was also studied in this report.

The thermal analyses found that the buffer thermal conductivity does not significantly influence the tunnel-wall temperature. However, the analyses showed that the buffer thermal conductivity does have a significant influence on the container-surface temperature during the first 100 years after waste placement.

The results demonstrate that the buffer composition and the resulting thermal conductivity is an important design consideration to optimize container and tunnel spacing within a Horizontal Tunnel Placement DGR, and to limit the container-surface temperature.