Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2009

NWMO TR-2010-01 **March 2010**

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Nuclear Waste Management Organization

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ABSTRACT

Title: **Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2009**
Report No.: **NWMO TR-2010-01**
Author(s): J. McKelvie, M. Ben Belfadhel, K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, A. Khan, E. Kremer, G. Kwong, T. Lam, H, Leung, P. Maak, C. Medri, A. Murchison, S. Russell, M. Sanchez-Rico Castejon, U. Stahmer, E. Sykes, A. Urrutia-Bustos, J. Villagran, A. Vorauer, T. Wanne and T. Yang
Company: Nuclear Waste Management Organization
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Abstract
This report is a summary of progress in 2009 for the Nuclear Waste Management Organization's (NWMO's) Technical Program. The Technical Program is supporting implementation of Adaptive Phased Management (APM), Canada's approach for long-term management of used nuclear fuel.

Significant technical program achievements in 2009 include:

- NWMO established an arrangement with the Canadian Nuclear Safety Commission to review and assess NWMO conceptual designs and safety for APM during the pre-licensing phase.

- The NWMO Independent Technical Review Group (ITRG) held their second review of the NWMO technical program. The ITRG noted significant developments in the work since 2008, and indicated that the program covers a full range of scientific and technical topics that are relevant to the current stage of APM. NWMO prepared an action plan addressing the recommendations of the ITRG report.

- NWMO continued to participate in international research activities associated with the SKB Äspö Hard Rock Laboratory, Mont Terri Rock Laboratory, Greenland Analogue Project, Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency Research Projects and the international working group on biosphere modelling (BIOPROTA).

- NWMO provided research contracts and research grants to 13 Canadian universities and, as an approved industrial partner with the Natural Science and Engineering Research Council of Canada, awarded 3 scholarships for Ph.D. students in 2009.

- The NWMO technical program expanded in 2009, with the addition of 7 new staff. NWMO's research program published 28 NWMO technical reports and 9 peer-reviewed journal articles.

- NWMO conducted research on: used fuel integrity; used fuel container corrosion; sealing material properties and their behaviour in the subsurface; and biosphere transfer processes. NWMO also continued to develop a repository monitoring and retrieval program and continued to survey developments in reprocessing and alternative waste management technologies.

- NWMO initiated projects to refine engineering conceptual designs, cost estimates, transportation logistics and implementation schedules in support of APM. These projects will be completed in the 2010/2011 time period.

- NWMO developed a set of technical site evaluation criteria and a stepwise site evaluation process to support the draft Site Selection Process Proposal for public review.

- The NWMO geoscience program continued to develop and assess laboratory and field characterization tools and methods in support of the site selection process. These included methods pertaining to: geophysical investigation; assessment of seismicity; matrix porewater characterization; assessment of radionuclide transport processes; fracture network modelling; and assessment of excavation damage zones.

- NWMO also continued to develop numerical modelling methods and continued to assess long-term geosphere stability associated with glaciations, seismicity and deep groundwater flow systems.

- NWMO continued to maintain and improve models and data suitable for supporting the safety assessment of potential sites and designs. In 2009, models assessing the waste form, repository, geosphere and biosphere were improved and maintained.

- A glaciation scenario safety assessment was completed for a deep geological repository for used nuclear fuel. Preparatory work was conducted in 2009 for the "Fourth Case Study" which will examine the updated used fuel repository design (with in-floor placement of larger containers) at a hypothetical site in crystalline rock.

- NWMO staff gave invited lectures at several Canadian Universities and organized and chaired sessions at the Spent Fuel Workshop (Toronto, 7-8 May, 2009) and the American Geophysical Union Joint Assembly (Toronto, 24–27 May, 2009).

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM), the approach selected by the Government of Canada in 2007 for long-term management of used nuclear fuel. The NWMO's Technical Program is refining and further developing generic engineering designs and safety cases in support of APM and is developing plans and methods to assess the suitability of willing host communities for a deep geological repository for used nuclear fuel (Figure 1.1). NWMO is conducting technical research to ensure continuous improvement and consistency with best practices.

A summary of progress in 2009 for the APM Technical Program is described in this Annual Technical Report.

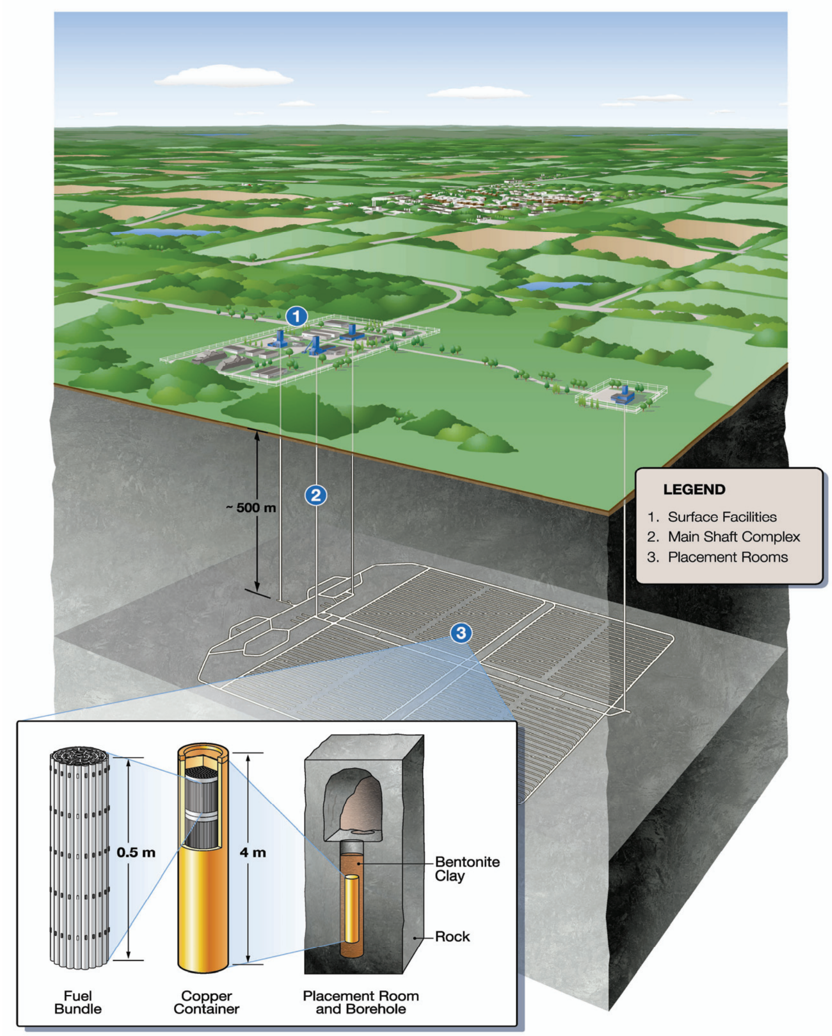

Figure 1.1: Conceptual design of a deep geological repository for used nuclear fuel.

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 (DGR), are regulated by the Canadian Nuclear Safety Commission (CNSC), under the *Nuclear Safety and Control Act (NSCA)*. 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.

A facility for long term management of used fuel is subject to all of the requirements of nuclear safety and security and safeguards embodied in the *NSCA* and its associated Regulations. Also applicable is the CNSC's Regulatory Policy P-290, *Managing Radioactive Waste* which 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.

CNSC's Regulatory Guide G-320, "*Assessing the Long Term Safety of Radioactive Waste Management",* describes approaches for assessing the potential impact that long-term radioactive waste management methods may have on the environment and on the health and safety of people.

The application for a CNSC licence for a DGR 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.

For the pre-licensing phase, the CNSC established a special project arrangement with the NWMO in March 2009 which includes CNSC review of NWMO information on conceptual APM design to identify any regulatory concerns. CNSC staff have expressed their general concurrence with the NWMO plan for obtaining CNSC staff review of APM conceptual design and illustrative safety assessments in representative host rock formations, one in crystalline rock and one in sedimentary rock. The plan aims at obtaining a CNSC statement on long-term safety of the conceptual design in both potential host rock formations by December 2012.

2.2 TECHNICAL PROGRAM OBJECTIVES

A strong technical 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 program are to:

(1) Prepare updated generic reference designs, cost estimates and safety cases for a deep geological repository in crystalline rock and in sedimentary rock by 2012;

(2) Further improve the reference designs for a deep geological repository in crystalline rock and in sedimentary rock;

(3) Further increase confidence in the deep geological repository safety cases;

(4) Obtain CNSC pre-licensing review of reference designs and safety cases for a deep geological repository in crystalline rock and in sedimentary rock by 2012;

(5) Enhance scientific understanding of processes that may influence repository safety;

(6) Evaluate the adequacy of potential candidate sites for a deep geological repository by conducting site characterizations and safety evaluations; and

(7) Maintain awareness of advances in technology development and alternative methods for long-term management of used nuclear fuel.

The repository engineering design, geoscience and repository safety technical program activities are described in more detail in Sections 3, 4 and 5, respectively.

The Independent Technical Review Group (ITRG) held their second meeting with NWMO staff and presented their review findings in an October 2009 report to the NWMO Board of Directors and Advisory Council. The ITRG noted significant developments in NWMO research and indicated that the program covers a full range of scientific and technical topics that are relevant to the current stage of APM. In February 2010, NWMO prepared an action plan addressing the recommendations of the ITRG report. The ITRG report and NWMO action plan can both be found at www.nwmo.ca.

A list of the technical reports produced by NWMO in 2009 is provided in Appendix A.1. Their respective abstracts are provided in Appendix B. All technical reports published before 2000 are listed in Garisto (2000), while the 2000 to 2008 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, Kremer et al., 2009). Note that prior to 2007, the technical program was managed by Atomic Energy of Canada Limited and then by Ontario Power Generation.

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

Appendix A.3 provides a list of graduate students awarded industrial postgraduate scholarships by NWMO in collaboration with the Natural Sciences and Engineering Research Council of Canada.

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

2.3 INTERNATIONAL ACTIVITIES

An important part of the NWMO's technical program is interacting with the corresponding national radioactive waste management organizations in other countries. The NWMO has 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 regulatory approvals.

Since 2004, Canada has been participating in experiments associated with the SKB Äspö Hard Rock Laboratory. The purpose of this participation is to improve our understanding of key processes in a repository in crystalline rock through implementation of large-scale projects, and to directly share lessons learned in repository technology development and site characterization. Specifically, in 2009, NWMO participated in the:

- Bentonite Colloid Transport Project;
- LASGIT Gas Injection Test;
- Engineered Barrier System Modelling Task Force;
- Groundwater Modelling Task Force;
- Canister Retrieval Test; and
- Backfill and Closure (BACLO) Project.

In 2009, NWMO continued its participation as a partner in the Mont Terri rock laboratory in Switzerland. 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). NWMO is currently involved in the following experiments within the Mont Terri Project:

- Disturbances, Diffusion and Retention (DR-A);
- 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) ;
- Mine-by Tests (MB); and
- Full Scale Emplacement Demonstration (FE).

To advance the understanding of the impact of glacial processes on the long-term performance of a DGR, the Greenland Analogue Project, a four-year field and modeling study of the Greenland ice sheet (2009-2012), was established collaboratively by SKB, POSIVA and NWMO. The Greenland ice sheet is considered to be an analogue of the conditions that are expected to prevail in Canada and Fennoscandinavia during future glacial cycles.

NWMO continued to participate in the international radioactive waste management program of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency. Members of this group include all the major nuclear energy countries, both waste owners and regulators. In particular, NWMO participated in the Integration Group for the Safety Case (IGSC) Methods for Safety Assessment (MeSA) Project, the Thermochemical Database (TDB) Project and the Radioactive Waste Management Committee (RWMC) Reversibility & Retrievability Project.

NWMO also continued its participation in BIOPROTA, the international working group on biosphere modelling, which included support to studies on selenium.

3. REPOSITORY ENGINEERING

3.1 INTRODUCTION

The main objectives of the repository engineering program are to: (1) Develop the engineering data, models, methods and tools necessary for the conceptual designs for a deep geological repository (DGR) and associated systems; (2) Provide engineering input to assess the safety of the DGR concept; (3) Support planned site characterization and investigation activities; and (4) 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 its achievements in 2009 are outlined for work activities related to research on used fuel integrity, container corrosion (including microbial induced corrosion), repository sealing material development and repository design (including DGR monitoring, container retrieval and transportation of the used fuel to the repository site).

3.2 USED FUEL INTEGRITY

As of June 30, 2009, approximately 2.1 million used Canadian Deuterium Uranium (CANDU) fuel bundles were in storage at Canadian reactor sites (Garamszeghy, 2009). The structural integrity of the CANDU fuel bundle (Figure 3.1) is important to its post-storage phase. Maintenance of fuel bundle integrity will ensure that routine transportation and handling of the fuel in subsequent steps of the Adaptive Phase Management (APM) strategy remain safe and efficient.

Significant progress was achieved in 2009 in the Fuel Integrity Program. This included:

- Improvements to the Bundle Stress Model and validation testing;
- Expansion of the database on delayed hydride cracking of endplate/endcap welds to include commercial 28- and 37 element unirradiated CANDU fuel bundles from two Canadian manufacturers (General Electric and Cameco); and
- Assessment of the effect of weld morphology on computed stress intensity factors for the endplate/endcap welds.

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

3.2.1 Bundle Stress Model Verification and Sensitivity Analysis

In 2009, validation and verification tests of the Bundle Stress Model continued and several improvements to the model were implemented. Previously found discrepancies between the Bundle Stress Model and test data from CANDU fuel bundles under bending loads (Snell, 2009; Lampman et al., 2009) were further investigated by testing the deformation of single fuel elements.

A reference test which examined the deformation of a cylindrical solid bar with dimensions identical to those of a single fuel element was performed. The results of the test were compared against an analytical solution and a modelled solution using ANSYS software. The predictions of the models were in excellent agreement with the experimentally-derived test data.

Bending load tests were also performed on single fuel elements from typical 28- and 37-element CANDU fuel bundles in a modified version of the apparatus used in the 2007-2008 tests on fuel CANDU fuel bundles. The test results were compared against a modified version of the fuel element model using the ANSYS platform. In the new version, the ANSYS finite element INTER195 was used as an interface between the fuel pellets and the cladding to transmit normal loads to the interface. It was found that excellent predictions of the test data could be made with this improved version.

A study using the Bundle Stress Model was also initiated in 2009 to estimate stress intensity factors at the endplate/endcap welds of 28-element CANDU fuel bundles when stored in Ontario Power Generation Inc. (OPG) storage modules under dry storage conditions at temperatures of 150°C. Results of this study are expected in 2010.

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

In 2009, the work program assessing the susceptibility of non-irradiated commercial CANDU fuel bundle endcaps and endplate welds to delayed hydride cracking (DHC) was expanded. There are currently two manufacturers of CANDU fuel bundles: General Electric (GE) and Cameco Zircatec. GE manufactures both 28- and 37- element bundles while Cameco manufactures 37- element Bruce type bundles. Two empty but fully manufactured GE bundles and one Cameco bundle were acquired for testing.

In addition to testing of the outer elements endplate/endcap welds for susceptibility to DHC, a finite element model was developed to compute threshold stress intensity factors at the welds for bending loads that initiate the process of DHC cracking. One particular aspect of the 2009 work was to study the impact that weld morphology has on the computed stress intensity factors. This work was required following observations from earlier work that indicated a variation on the weld morphology of tested endplate/endcap welds.

Testing of the endplate/endcap welds of the GE and Cameco fuel bundles was done in a previously developed test apparatus (Shek et al., 2009). The experimental campaign is near completion and documentation of the test results is expected to be completed in 2010. Preliminary results indicate that stress intensity factors for the GE and Cameco bundles are similar to the values found in 2008 for the one GE bundle.

3.2.3 ORIGEN-S Decay Heat Calculations for CANDU Fuel Bundles Stored in the Temperature Monitored Storage Container (DSC-812)

The thermal performance of an OPG Dry Storage Container (DSC-812) has been monitored during its processing and storage after 384 sixteen year old CANDU fuel bundles were loaded in the DSC in 2007. DSC-812 is located at the Dry Storage Facility of the Western Waste Management Facility (WWMF) at the Bruce site. The purpose of this study is to further investigate used fuel integrity and to conduct a thermal analysis of the DSC.

A key source of information to proceed with the thermal analysis of DSC-812 is the heat of decay of the stored fuel bundles. To reduce the effort in the determination of the heat of decay values for the 384 CANDU fuel bundles stored in the DSC, a statistical analysis on the whole bundle population stored in the DSC was performed to identify representative bundles for the heat of decay evaluation. The analysis was based on nominal bundle data that included the discharge time and the content of ^{235}U and plutonium provided by the station. The results of the analysis identified 22 representative bundles for detailed calculations on burnup and heat of decay using the ORIGEN-S code. Data input into the ORIGEN-S code included fuel bundle accounting data from the NuFLASH code and bundle power history from the production physics database (SORO).

The results from the ORIGEN-S code indicate that the heat of decay for bundles after 10 years of storage is nearly independent from the bundle power history and mostly dependent on the fuel bundle burnup. A linear correlation was developed between heat of decay and burnup for the 22 selected bundles. The correlation will simplify obtaining the heat of decay for the remaining bundles once their burnup values are determined. The results of this work are published in the NWMO report by Seager and Inglot (2009).

3.3 CONTAINER CORROSION

3.3.1 Copper Corrosion

The schematic of a copper used fuel container designed for use in a DGR is shown in Figure 3.2. Copper corrosion work in 2009 continued to focus on the investigation of stress corrosion cracking (SCC) of copper. The objectives were to improve the current knowledge of copper SCC in a repository environment and to determine the boundaries of the environmental parameters affecting SCC of copper. Experiments carried out in 2009 studied the SCC behaviour of oxygen free phosphorous doped copper in nitrite solutions. Preliminary results suggest that SCC was evident in the range of deaerated nitrite concentrations between 0.1 $mol.L^{-1}$ and 1.0 $mol.L^{-1}$, at an applied current of $1 \mu A.cm^{-2}$. Under these conditions, a possible threshold concentration of 0.04 $mol.L^{-1}$ chloride was observed to suppress SCC in nitrite concentrations ≤ 1.0 $mol.L^{-1}$. The role of chloride in suppressing SCC is likely due to the promotion of uniform corrosion and disruption of oxide film formation on the crack surface by chloride. Surface analyses using Raman Spectroscopy, X-Ray Photoelectron Spectroscopy (XPS) and Scanning Electron Microscopy coupled with Energy Dispersive X-Ray (SEM/EDX) are currently in progress to obtain further information of the crack surface.

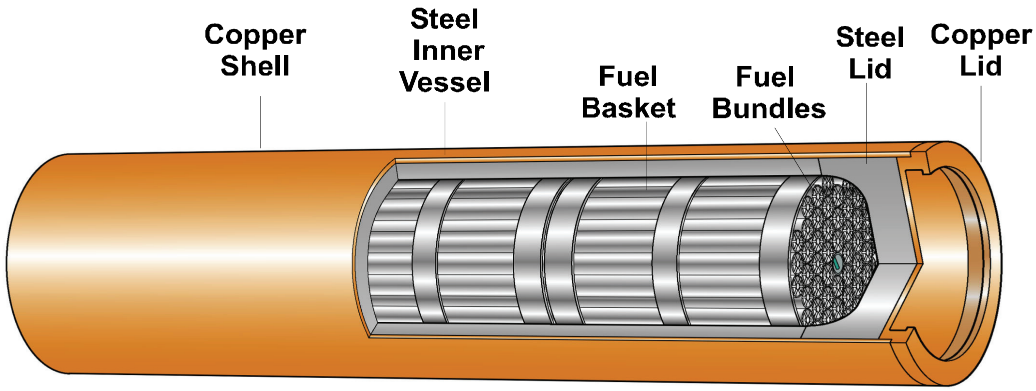

Figure 3.2: Copper used fuel container.

3.3.2 Steel Corrosion

In 2009, corrosion experiments designed to evaluate the anaerobic corrosion behaviour of carbon steel continued at the University of Toronto. (Carbon steel is being evaluated as an alternative corrosion barrier material for a used fuel container). These experiments measured the amount of hydrogen generated from anaerobic corrosion of carbon steel under different relative humidity environments using: (1) A high sensitivity pressure gauge; and (2) A solid-state potentiometric hydrogen sensor. Preliminary results indicate a corrosion rate of < 0.5 μm.a^{-1} and < 0.1 μm.a^{-1} in the presence and absence of chloride, respectively in an unsaturated, anoxic environment. Significantly lower corrosion rates were observed for pickled carbon steel surfaces for which observed corrosion rates were often several orders of magnitude lower than the rates of the NaCl covered surfaces. Additional results and interpretations are expected in 2010, which will be used to refine the lifetime predictions of carbon steel used fuel containers (UFCs) and to improve the existing knowledge of hydrogen gas evolution from the UFCs in a DGR.

Other 2009 work activities related to carbon steel corrosion included the development of a corrosion model to predict the anaerobic behaviour of carbon steel in both saturated and unsaturated conditions (King and Kolar, 2009) and completion of a literature review assessing the hydrogen-related degradation effects on carbon steel UFCs under the anticipated repository environment (King, 2009). The review evaluated the various aspects of possible hydrogen-related damage to carbon steel UFCs and concluded the most likely forms of H damage are blister formation or hydrogen-induced cracking and cracking associated with the inner surface of the closure weld once gaseous hydrogen has entered the void space inside the container. While the failure risk caused by hydrogen damage may be controlled by proper specification of the steel grade and a proper design of the closure weld, hydrogen-related damage to carbon steel UFCs remain possible for the vast majority of the container design lifetime.

To improve the understanding of hydrogen effects on carbon steel over long-term anaerobic conditions, further work to investigate adsorption rates, concentrations, and distribution of hydrogen in carbon steel over time was proposed.

3.4 SEALING MATERIAL DEVELOPMENT

In 2009, the NWMO continued to assess the properties of bentonite-based sealing materials through several laboratory and modelling studies. Tests were carried out on the following sealing materials that are being considered for use in a DGR: (1) Highly compacted bentonite (HCB) – 100% bentonite clay; (2) Bentonite-Sand Buffer (BSB) – 50% bentonite and 50% sand by mass; (3) Dense Backfill (DBF) – 70% crushed granite, 25% lake clay and 5% bentonite by mass; (4) Light Backfill (LBF) – 50% bentonite and 50% crushed granite by mass; and (5) Gapfill (GF) – 100% bentonite clay 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. As a component of this program, a total of seventeen testing cells were commissioned in order to examine the process of water uptake and volumetric equilibrium of backfill clay blocks in contact with clay pellets. These tests are scheduled to be dismantled at intervals of 3, 9 and 27 months with associated measurement of gravimetric water content and volume changes of the components installed (expansion or compression). Twelve testing cells for 3- and 9-month periods have been dismantled since July 2008 and five testing cells scheduled for 27-months of operation are still being monitored. At the end of this testing program, data will be available on the evolution of the internal gravimetric water content and density. This information will be useful to provide a better understanding of the role of groundwater salinity on the clay-based sealing materials.

3.4.1 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 of barrier materials that contain swelling clay minerals (Dixon, 2000). 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 in Canadian groundwaters according to Gascoyne et al. (1987) and Mazurek (2004).

In order to characterize elastic and critical state parameters under saturated saline water conditions, the NWMO has carried out a long-term triaxial testing program on LBF and DBF material with saline ($CaCl_2$) water as the pore fluid. These mechanical properties are important parameters for numerical modelling. In 2009, the results showed an increase in strength when LBF is saturated with saline pore fluid (227 g/L $CaCl_2$). The Mohr-Coulomb peak friction angle increased from a value of 13° under fresh water conditions to 20° with saline pore fluid conditions. The initial results of tests conducted on DBF made with saline pore fluid (250 g/L $CaCl_2$) suggest that the strength and deformation characteristics of DBF are not highly sensitive to increases in pore fluid salinity. The Mohr-Coulomb peak friction angle for this material is 28° under both fresh water and saline pore fluid conditions.

In addition to the triaxial testing program, a 1D consolidation testing program has been carried out on HCB, DBF, and LBF using four types of fluid solutions, Distilled Water (DW), $CaCl_2$, NaCl, and Na-Ca-Cl in order to define the behaviour of clay-based sealing materials for future use in numerical modelling. The salinity has been used as either fluid for specimen preparation or reservoir fluid, with concentrations as high as 250 g/L. Two different boundary conditions were applied during initial saturation, either constant volume (CV) or constant vertical stress (CS), in order to examine the effect of the boundary condition during initial saturation on the material performance. The 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 pore fluid solution concentration, independent of the type of salt solution (i.e., $CaCl_2$, NaCl or Na-Ca-Cl).

The replication of laboratory results using numerical models is a step in the process of developing techniques for modelling engineered barrier systems under repository conditions. Modifications to existing constitutive models for hydraulic and mechanical behaviour of compacted BSB material in unsaturated conditions have been introduced by Priyanto and Dixon (2009). This model is able to replicate the results of laboratory tests, where maximum gravimetric water content (w) is linearly dependent on the total porosity. Parameters used in the models have been applied to simulate the infiltration process in triaxial specimens under CV and constant mean stress (CMS) tests using three different computer codes based on the finite element methods (i.e., CODE_BRIGHT and COMSOL) and finite difference methods (i.e., FLAC).

An example of the simulation is shown in Figure 3.3 where changes in the degree of saturation contours during constant volume tests for analyses using FLAC-BSB are presented. The analysis shows an increase in the degree of saturation starting with the outer surface. At the end of test in the FLAC-BSB analysis 100% saturation is almost reached. One of the general conclusions of the modelling is that the elasto-plastic model results in variation of dry density at the end of the test (equilibrium), which can improve the matching of laboratory test results. The elasto-plastic models also can improve the matching of total mean stress.

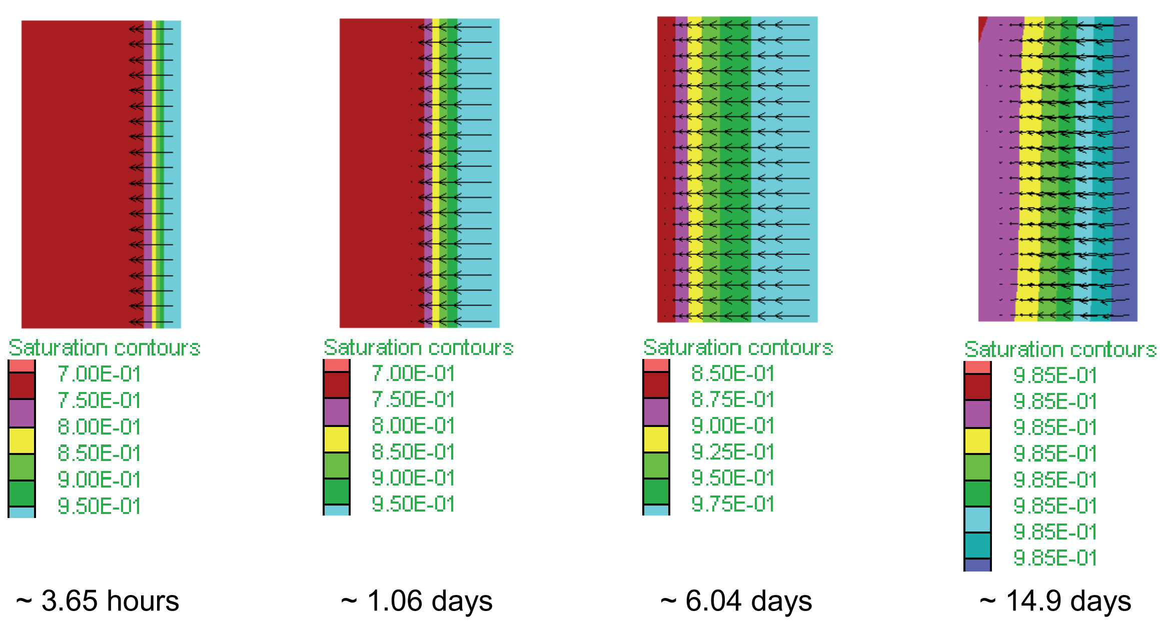

Figure 3.3: Degree of saturation contour from FLAC-BSB model analysis (Constant Mean Stress). From Priyanto and Dixon (2009).

3.4.2 Thermal-Mechanical-Hydraulic Properties of Sealing System Components

A large amount of work has been invested in developing an understanding of the properties of materials used in engineered barrier systems for nuclear used fuel isolation in Canada and internationally. Clay based sealing materials have been designated by function and material. Cement based material is primarily designated as concrete, specifically as low alkalinity concrete, but cement based materials may also be used in grouting applications. Knowledge of the properties and behaviour of these materials are required to evaluate and model the performance of the overall repository sealing system.

The known properties and behaviour of sealing system materials were summarized by Baumgartner (2006) and more recently by Man and Martino (2009). As all natural materials vary, the details of the specific materials are identified when available. Not all properties of these materials have been determined and these gaps were identified in order to guide future material testing programs.

In addition to identifying the behaviour of engineered barrier systems, NWMO has begun to assess the issues associated with bentonite/sand pellet preparation and the knowledge gaps that exist for both the In-Floor-Borehole (IFB) and the Horizontal Tunnel Placement (HTP) methods in order to improve the thermal conductivity of the placement systems.

3.4.3 Microbial Studies in Repository Sealing Systems

3.4.3.1 Experimental Studies Assessing Microbially Influenced Corrosion and Survivability

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 DGR. Previous microbial investigations, supported by NWMO, investigated the culturability of microorganisms in buffer and sealing materials and found that heterotrophic aerobes, anaerobes and sulphate-reducing bacteria were present in the studied materials (Stroes-Gascoyne, 2010). Additional studies examined the effects of dry density and porewater salinity on indigenous viable microbial communities in bentonite (Stroes-Gascoyne et al., 2010) to assess their ability to suppress microbial activity and therefore potentially reduce microbially influenced corrosion (MIC).

Microbial activity can cause MIC which may affect the service life of used fuel containers in a repository. An important role of highly compacted bentonite is the reduction of significant microbial activity near the used fuel containers in a DGR, which would reduce or eliminate the possibility of MIC. In the current work program, microbial experiments and analyses were carried under elevated temperatures in the range of 80 to 130^{o}C. The results suggest that phospholipid fatty acid (PLFA) is a good biomarker for viable cells in high water activity, biologically active environments. In environments that are biologically inactive, PLFA can persist, which implies that PLFA may indicate dead microbial biomass. In such environments, PLFA content only indicates potentially viable microbial biomass and other methods need to be developed to determine with more certainty whether such environments contain viable cells in the quantities indicated by the PLFA content. The results also suggest that in both low and high dry density compacted bentonite plugs, some culturability remained after exposure to 80^{o}C. Cells in the low dry density saturated compacted bentonite plugs did not remain culturable at temperatures of 121^{o}C and above, but cells in the high dry density saturated compacted plugs bentonite did maintain some culturability, even after exposure to 130^{o}C. The differences in remaining culturability confirm that vegetative cells are more sensitive to the detrimental effects of elevated temperature than dormant cells or spores.

Microbial experiments were carried out to assess whether the salinity effects on microbes indigenous to Wyoming MX-80 bentonite in saline Ca-dominated porewaters, would be similar to those determined with NaCl porewaters in previous work (Stroes-Gascoyne et al., 2010). The results show that aerobic culturability results obtained for porewaters with $CaCl_2$ are largely similar to the NaCl porewater results, as expected. Figure 3.4 shows culturable aerobes as a function of porewater salinity and compares all previous NaCl data with the new $CaCl_2$ data, for all dry densities (0.8-2.0 g/cm^3) used.

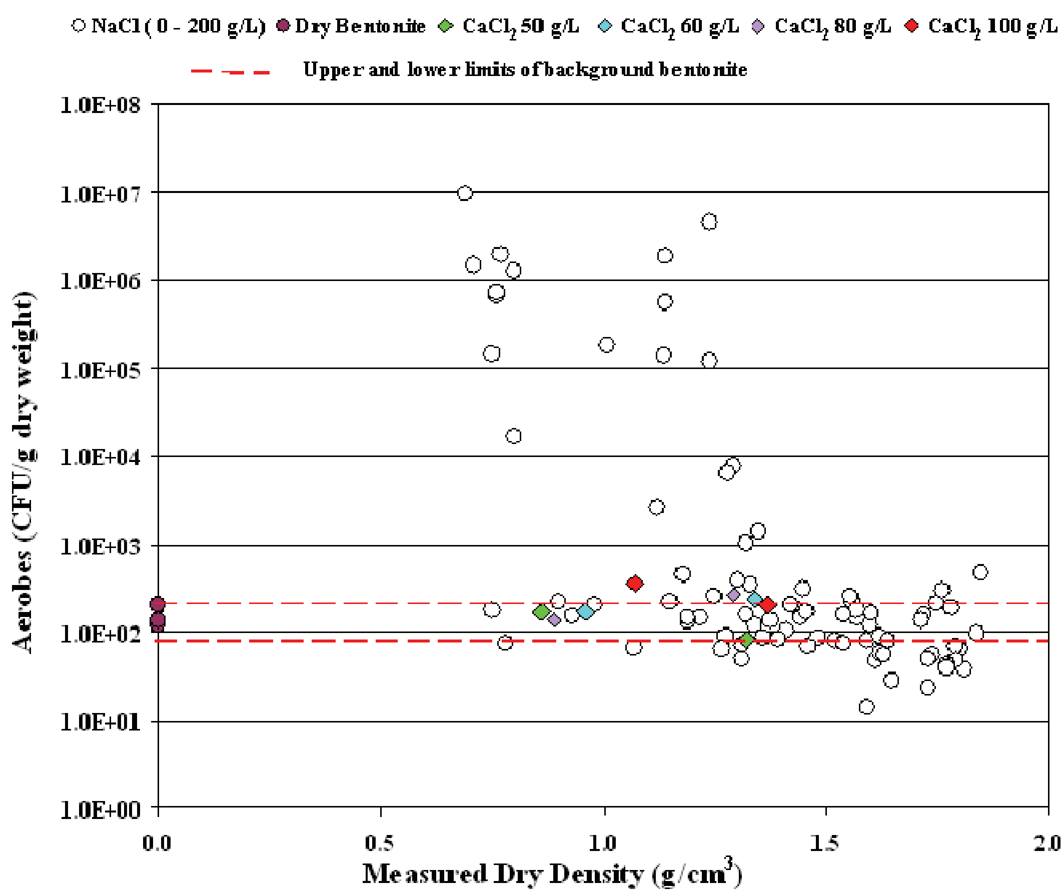

Figure 3.4: Comparison of heterotrophic aerobes as a function of measured dry density in compacted bentonite infused with porewater containing NaCl (0 - 200 g/L) or $CaCl_2$ (50, 60, 80 and 100 g/L) ($CaCl_2$ data shown in colour).

3.4.3.2 Characterization of Microbial Communities in the Opalinus Clay

Microbial analyses were performed on specific Opalinus clay core samples from the Mont Terri Underground Rock Laboratory, for the presence of indigenous bacteria. The core samples were drilled in April, 2009 from the borehole BHT-1 of the Hydrogen Transport Test. The drilling was conducted under clean, but not entirely aseptic conditions, and using air for the first 9 m and Ar for the last 6 m. The results suggest: (1)The presence of only a small, largely inactive microbial population; (2) Local variations in biomass and physical parameters such as water content and water activity; and (3) A high probability of contaminating microbial species from the drilling process.

3.4.4 Quarried Block Experiment – Bentonite Colloid Transport

The goal of the Colloid Transport Project is 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 repository, such as in a glacial meltwater intrusion scenario. This experiment has been undertaken collaboratively with SKB in support of their bentonite colloid program and in support of the in situ Colloid Formation and Migration (CFM) experiment at the Swiss Grimsel test site.

In 2007, bentonite and latex colloid migration experiments where completed in a 1 x 1 m natural fracture in the Quarried Block sample at Atomic Energy of Canada Limited's (AECL's) Whiteshell Research Laboratories. The findings from these experiments are reported in Vilks and Miller (2009). In 2008, a series of laboratory-scale bentonite erosion and colloid transport experiments were conducted in a Plexiglass fracture with a consistent aperture of either 5 or 1 mm. The results were used to plan the 2009 Quarried Block (QB) experiments, which were conducted in a 1 x 1 m natural fracture with a known and detailed aperture distribution. The experimental plan included: (1) Characterization of the transport properties of the Quarried Block (QB) fracture with a series of solute tracer tests to provide a benchmark for colloid transport modelling and for assessment of the impact of aperture modification associated with bentonite expansion and transport; (2) Placement of compacted, MX-80, bentonite plugs in both a large aperture and small aperture zone of the QB fracture, each plug being prepared with either fluorescent yellow-green or red, 200 nm, latex colloids as tracers; (3) A complete erosion experiment in a dipole flow field (44 mL/h) using synthetic Grimsel water as a proxy for glacial meltwater, while analyzing elution water for bentonite and latex tracer; (4) Repetition of selected solute tracer tests after the bentonite erosion experiment to determine whether eroded bentonite has altered transport within the QB; and (5) Complete post-test analysis of the fracture surfaces to visualize the extent of bentonite erosion from each plug.

The direction of fracture slope plays an important role in determining the direction of bentonite movement, as shown in Figure 3.5 and as observed during the 2008 mock-up tests. Even thought the flow rate imposed during the erosion experiment was higher than what would be expected under natural conditions, based on post-test sampling, almost all of the original bentonite remained in or adjacent to the borehole as illustrated in Figure 3.5. Although limited, the extent of bentonite expansion and movement into the fracture was sufficient to alter the nature of tracer transport in the fracture as determined from comparing pre- and post-experiment, tracer tests. Finally, the results of the Quarried Block erosion test indicate that in water containing millimolar amounts of dissolved salts (representative of glacial melt water) the bentonite that expands into an open fracture is likely to form stable deposits that do not release significant concentrations of bentonite colloids.

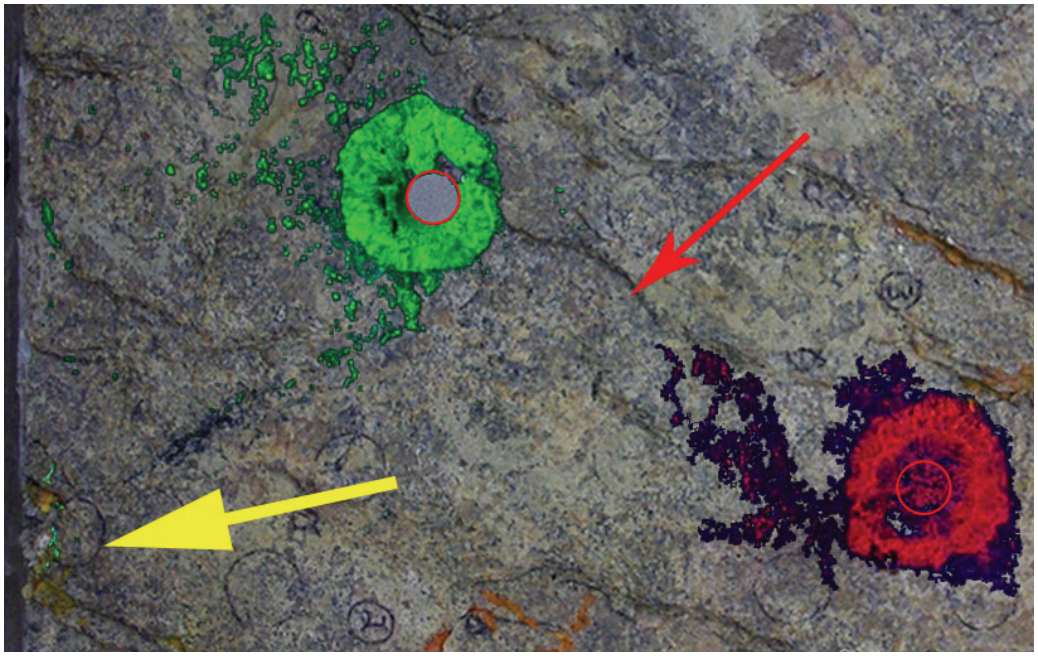

Figure 3.5: Close up of L1 and L3 bentonite plugs. Fluorescence marks extent of bentonite movement superimposed on the bottom fracture surface. Red circles show extent of bentonite plugs (38 mm diameter) before saturation and expansion. Yellow arrow shows dip direction and red arrow indicates the approximate flow direction.

3.5 REPOSITORY DESIGN

In 2009, the NWMO initiated a study to update the generic conceptual designs, implementation schedules and cost estimates for an APM approach that includes a DGR for used fuel in crystalline or sedimentary rock. The update includes associated facilities at the repository site, and the systems for transporting used fuel from current storage locations to the repository site.

The base case assumes a used fuel inventory of 3,600,000 used fuel bundles and the alternative case assumes a used fuel inventory of 7,200,000 used fuel bundles. The preliminary requirement is that the packaging and placement rate will be about 120,000 used fuel bundles/year. To evaluate the sensitivity of the cost estimate for the APM transportation system and DGR to variances in host rock type and placement method, conceptual designs and cost estimates are being prepared for the following DGR options and placement methods:

a) The repository is assumed to be excavated in crystalline rock with the placement level at a depth of 500 m using the in-floor borehole placement method for used fuel containers; and
b) The repository is assumed to be excavated in sedimentary rock with a placement level at a depth of 500m using the horizontal tunnel placement method for used fuel containers.

The 500 m depth is within the assumed range for repository depths for generic DGR studies in crystalline and sedimentary rock.

3.5.1 Numerical Modelling of a Deep Geological Repository

Thermal and thermal-mechanical models were developed using CODE_BRIGHT for a DGR for used CANDU fuel assumed to be located at a depth of 500 m in crystalline rock using the in-floor borehole placement method (Guo 2009a). Near-field thermal analyses were carried out to develop a number of thermally acceptable repository layouts. A specific repository layout design with a container spacing of 4.2 m and a placement room-spacing of 40 m was selected and applied for excavation stability analyses. This specific repository layout design requires the shortest total length of placement rooms and access tunnels. Excavation-induced mechanical stresses in the rock around the placement room and the placement borehole were studied for circular and elliptical shaped placement rooms. Excavation of placement room would not cause any significant failure in the rock surrounding the placement room. However, drilling the in-floor boreholes within the placement room could cause localized damage at the roof of the placement room, around the boreholes and in the rock web between two adjacent boreholes. In comparison with the elliptical-shaped room, the localised damage is more severe in the circular-shaped room.

The development of a numerical model to assess and predict excavation stability of a horizontal tunnel in a DGR located in shale and limestone commenced in 2009. The model is expected to be completed in 2010.

3.6 MONITORING

3.6.1 Development of a Repository Monitoring Program

A draft program plan on Repository Monitoring was prepared in December 2009. It constitutes a roadmap for developing NWMO's Repository Monitoring work program for the next few years. The contents of the program plan, which will developed further in 2010, incorporate the staged development of Monitoring concepts and strategies in consultation with the public and other APM stakeholders. It is envisaged that the evolution of this program will be guided by continued NWMO engagement and consultation activities.

3.6.2 Enhanced Sealing Project

The Enhanced Sealing Project (ESP) is an international full-scale shaft seal demonstration and monitoring project, being conducted at Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory (URL) under a cooperation agreement between AECL, NWMO, ANDRA, POSIVA and SKB. Two composite concrete/bentonite seals were installed in the URL. One is located in the main access shaft and is instrumented for monitoring purposes, while the second seal installed in the ventilation shaft is not instrumented. The operational objective of these seals is to isolate the saline and fresh water aquifers at the URL site by limiting water mixing along the access shaft and the ventilation shaft. The seals consist of a bentonite clay-sand component, sandwiched between two massive concrete components. The concrete will be keyed into the access shaft and ventilation shaft walls to better anchor them in place in order to restrain the swelling of the bentonite clay as it hydrates. Figure 3.6 shows the location of the seals and Figure 3.7 illustrates the configuration of the seals. The design, construction and instrumentation of the seals are described by Dixon et al. (2009). A summary of project milestones is presented in Table 3.1.

Table 3.1: Enhanced Sealing Project Completed Tasks

Task	Main Access Shaft	Ventilation Shaft
Pre-installation grouting	2008 May 27 – May 28	2008 April 03
Excavate keys and beam notches	2009 May 26 – 2009 Jul 10	2009 Oct 19 – 2009 Nov 04
Install formwork and beams	2009 Jul 14 – 2009 Jul 21	2009 Nov 05 – 2009 Nov 12
Leveling pour	2009 Jul 21	2009 Nov 13
Install rebar	2009 Jul 23 – 2009 Aug 25	2009 Nov 18 – 2009 Nov 22
Lower Concrete pour	2009 Sep 01 – 2009 Sep 02	2009 Nov 26
Curing	2009 Sep 02 – 2009 Sep 30	2009 Nov 26 – 2009 Dec 23
Install clay	2009 Oct 06 – 2009 Nov 10	2010
Upper concrete Pour	2009 Nov 25 – 2009 Nov 26	2010

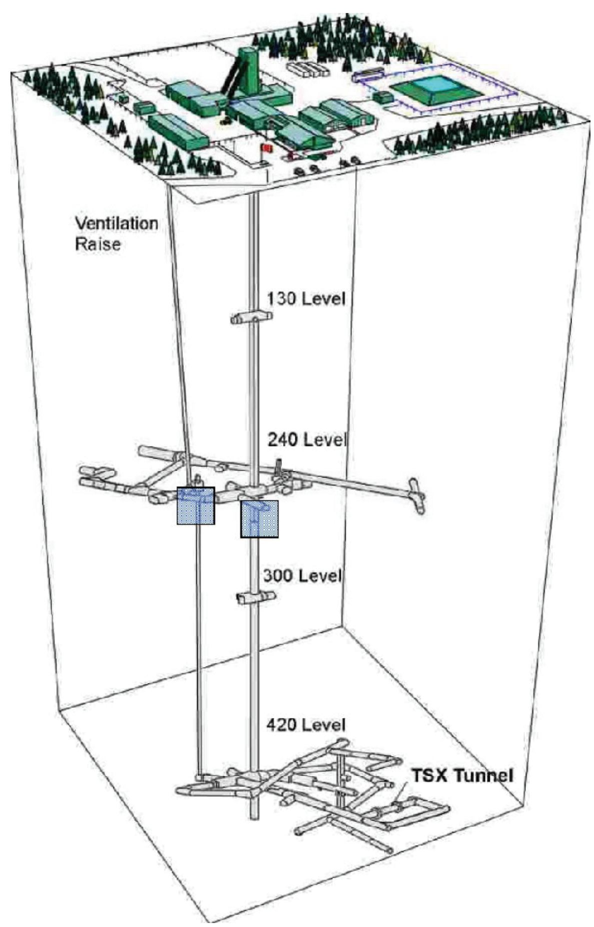

Figure 3.6: 3D diagram of the AECL URL showing the location (blue squares) of the shaft seals installed during 2009.

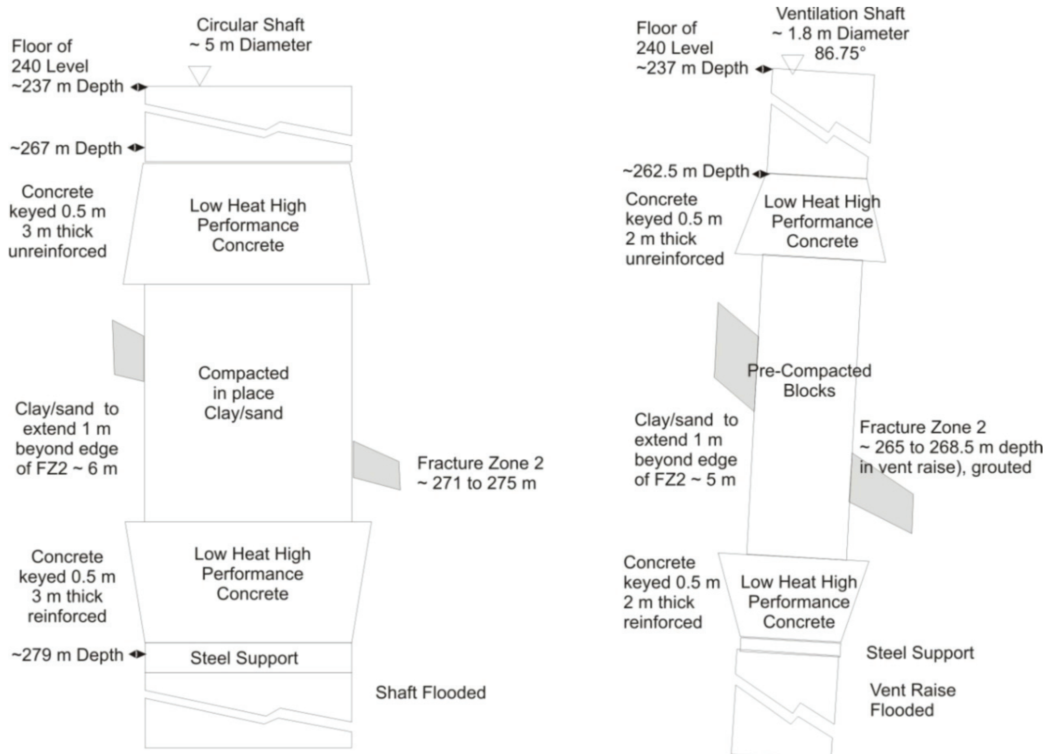

Figure 3.7: **Configuration of installed shaft seals used to isolate the shafts from fracture Zone 2 at the AECL URL.**

The lower concrete component in each seal is reinforced, as it must provide mechanical support for the installation of the clay seal. The lower concrete component in each seal will need to remain in place with only minor displacement (less than 0.05 m), as well as be self-supporting and bear the load of the sealing material and hydraulic head. The upper concrete unit does not require reinforcement.

The suite of sensors installed in the access shaft seal that will allow monitoring of the evolution of temperature, concrete-strains, porewater pressure, total stress, and water uptake by the clay component. The detailed locations of these sensors are described by Dixon et al. (2009). A list of the instruments mounted in each of the seal's components is given in Table 3.2. Data collection commenced in 2009 and will continue for one year under the ESP agreement. At that point further decisions will be made regarding future monitoring activities associated with the project.

Table 3.2: Instruments Installed in the ESP Shaft Seal

Parameter	Instrument
Lower Concrete Component	
Strain	5 Fibre-optic strain gauges
Temperature	5 Thermocouples
Hydraulic Pressure	2 Vibrating Wire piezometers with temperature
Clay component	
Water Content	Thermocouple psychrometers
	Time domain reflectometers
Pore Pressure	2 Vibrating Wire piezometer with temperature
	5 Fibre-optic piezometers
	3 Vibrating wire piezometers in near field rock
Total Pressure	2 Vibrating Wire Total pressure cells
	5 Fibre-optic total pressure cells
Upper Concrete Component	
Strain	5 Fibre-optic strain gages
Temperature	5 Thermocouples
Hydraulic Pressure	1 Vibrating Wire piezometer with temperature
Total Pressure	3 Vibrating Wire TPC's with temperature sensors

3.7 RETRIEVAL

Retrievability of used nuclear fuel for an extended period of time is a fundamental feature of APM, Canada's approach for long-term management of used fuel (NWMO, 2005). In developing APM and the potential for retrievability of used fuel, the NWMO conducted dialogues and engagement activities with interested citizens and participated in international working groups to discuss potential retrieval approaches or strategies.

Since 2008, the NWMO has been participating in the Nuclear Energy Agency (NEA) Working Group on Reversibility and Retrievability. The key objective of the NEA working group is to provide various NEA member countries a forum to share their experience and resources in the area of nuclear waste retrieval. Retrieval requirements, policy development and the decision making processes of the participating countries are discussed in these group meetings.

In 2009, NWMO participated in NEA international group meetings and participated in a preliminary review of retrieval technologies. This review assesses the currently available technologies for retrieving placed nuclear waste from a repository and/or successful retrieval techniques demonstrated at various international surface laboratories. More in-depth assessments of the current retrieval technologies that are suitable for the Canadian repository applications will continue in 2010. Information gathered will form the basis for the development of a plan in 2010 to further assess and evaluate used fuel retrieval.

3.7.1 Äspö Engineering Barrier Task Force

As part of NMWO's contribution to the Task Force on Engineering Barrier systems, the Canadian modeling team from AECL performed a modeling study using CODE_BRIGHT (Guo, 2009b). Thermal responses were successfully modelled for the bentonite materials and the granite using either the coupled thermal-hydraulic model or coupled thermal-hydraulic-mechanical (THM) model. The hydraulic response could also be modelled using coupled models. The trends of mechanical response development could be captured in the simulations. However, there were some challenges in obtaining a good match in absolute values. When a high porewater pressure boundary was applied to bentonite materials, there were some difficulties with convergence in coupled THM modelling because greater porewater pressure can cause greater tensile stress in the bentonite materials.

3.8 USED FUEL TRANSPORTATION

The objectives of the transportation program are to: (1) Develop and evaluate options for the transport of used fuel from interim storage sites to a hypothetical used fuel DGR site; and (2) Provide engineering design and logistics to support future technical evaluations of potential candidate repository sites. In the short-term, before feasibility studies have been completed and potential candidate sites have been identified, the transportation program objective is being addressed through the development of conceptual designs and illustrative case studies.

To provide a general understanding of used nuclear fuel transport, the state of used nuclear fuel transport programs within Canada and several countries that are leading the way in fuel transport was investigated and documented in a report by Stahmer (2009a).

3.8.1 Transportation System Conceptual Design

Used fuel transportation is included in the updated APM engineering design and cost studies and plays an integral part in Canada's plan for the long-term management of used nuclear fuel. In 2009, draft conceptual studies for the loading of transportation packages and their transport using roadways to the APM facility were prepared. These studies are on-going and will be completed in 2010. Future studies will consider the transport of used fuel by road, rail and water transportation modes.

3.8.2 Transportation System Logistics

In 2009, used fuel inventory estimates and transportation logistics were prepared to support the implementation of APM. Two used nuclear fuel inventory scenarios were considered: (1) A base case (assuming 3.6 million used CANDU bundles); and (2) An alternate case (assuming 7.2 million used CANDU bundles). The transportation logistics are presented in Stahmer (2009b).

3.9 REPROCESSING AND ALTERNATIVE WASTE MANAGEMENT TECHNOLOGY

Reprocessing is a general term for applying chemical and physical processes to used (or sometimes referred to as “spent”) fuel from today’s reactors to separate (**partition**) its components generally into the following streams:

- The metal fuel cladding materials that hold the nuclear fuel pellets;
- Uranium, which forms most of the fuel mass;
- Fissile isotopes such as plutonium-239, which can be recycled in fresh reactor fuels; and
- The fission products, minor actinides and other radioactive isotopes formed by neutron activation, which are radioactive wastes generally destined for placement in a deep geological repository.

Broadly speaking **transmutation** involves forcing the Minor Actinides to fission in an intense flux of high energy neutrons provided by a Fast Reactor and/or an Accelerator Driven System with the purpose of destroying them prior to placement of residual high-level radioactive wastes in a repository. These three activities are grouped together under the abbreviation RP&T.

The second annual watching brief on reprocessing of used fuel and alternative waste management technologies was published in 2009 (Jackson and Dormuth, 2009). The report summarizes the major developments in international RP&T programs, research and development on closed fuel cycles and progress on thorium fuel technology.

3.9.1 Costs of RP&T for CANDU Fuel

The 2009 watching brief included a review of RP&T costs, based on existing light water reactor (LWR) reprocessing plants, and concluded that capital and operating costs were on the order of $3,000 to $4,000 per kg of heavy metal (Jackson and Dormuth, 2009).

Using the used fuel reprocessing cost estimate prepared by Jackson and Dormuth (2009) and the 20 kg average heavy metal mass of a CANDU fuel bundle, a total cost of $250 to $320 billion CAD would be required to reprocess a reference inventory of 4 million fuel bundles. As well, there would be additional costs associated with the handling and long-term management of the associated residual high-level waste from reprocessing.

3.9.2 Very Deep Borehole Disposal

Jackson and Dormuth (2009) reviewed the very deep borehole concept for the long-term management of nuclear waste and provided cost estimates for the placement of 4 million CANDU fuel bundles. The very deep borehole concept consists of placing the waste packages 3 to 6 km deep in individual boreholes drilled from the surface. The borehole, up to perhaps one metre in diameter at its bottom, would be cased to allow waste packages to be lowered into place, one on top of another. With the waste in place, the borehole would be plugged and sealed from depth to the surface. Once sealed, the long-term safety of the system rests principally on the separation of the hydrogeological regime at the depth of the waste packages from that nearer the surface, and on the integrity of the borehole plugs and seals.

A preliminary evaluation of the safety of very deep borehole disposal of LWR used fuel in crystalline rock was carried out by Sandia National Laboratories (see Jackson and Dormuth (2009)). In the Sandia evaluation, the construction of a 5 km deep borehole is estimated to take 110 days and cost about $20 million USD. With the assumption that each borehole would contain about 400 LWR fuel assemblies, disposal of the projected 109,300 metric tonnes of heavy metal inventory would require about 950 boreholes. The estimated total life-cycle cost (including site characterization, licensing, disposal, monitoring, transportation, etc.) is $71 billion USD (2008 dollars).

4. GEOSCIENCE

4.1 INTRODUCTION

The geoscience program is developing plans and methods to assess the suitability of potential candidate sites in willing host communities and refining the understanding of geosphere processes related to the long-term stability and performance of a deep geological repository (DGR). The main objectives of the NWMO's geoscience program are to: (1) Develop and update geoscientific siting criteria to contribute to the evaluation of potential candidate sites; (2) Develop plans and methods for conducting preliminary and detailed geoscientific site evaluations in crystalline and sedimentary settings; and (3) Advance the understanding of geosphere stability and its resilience to long-term perturbations. 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. In particular, the geosciences program is a partner and participant in the Äspö Modelling Taskforce, Greenland Analogue Project and Mont Terri Underground Rock Laboratory Project.

The focus of NWMO work in 2009 was to continue developing readiness for evaluating potential candidate sites in willing host communities, focusing on the early stages of the site evaluation process. This includes the development of geoscientific criteria, the development of generic plans for conducting initial screenings and feasibility studies, and a number of other activities that would support various phases of the site evaluation process. NWMO staff continued to acquire practical field investigation experience relevant to a DGR from involvement in Ontario Power Generation's proposed Low and Intermediate Level Waste DGR. This included the planning and execution of detailed site characterization activities, collection, management and integration of geoscientific data and quality assurance.

The following sections outline the activities of the geoscience work program in 2009. The activities are organized into sections describing the development of site evaluation plans and methods (Section 4.2), assessment of long-term geosphere stability (Section 4.3) and development of numerical tools and methods (Section 4.4).

4.2 DEVELOPMENT OF SITE EVALUATION PLANS AND METHODS

In 2009, the NWMO issued a siting process proposal for public review "*Moving Forward Together: Designing the Process for Selecting a Site*" (NWMO, 2009). The proposal included a list of site evaluation criteria and a site evaluation process. It is anticipated that the suitability of potential candidate sites to safely host a DGR will be evaluated over many years in a stepwise approach. Each step is designed to evaluate the site in greater detail than the previous step as follows:

(1) Initial Screenings to evaluate the suitability of candidate sites against a list of initial screening criteria, using readily available information;

(2) Feasibility studies to determine if candidate sites may be suitable for developing a safe used fuel repository. These studies will be conducted in the form of desktop studies using available geoscientific information, but may also involve limited field investigations to increase confidence in the potential suitability of the sites; and

(3) Detailed field investigations to confirm suitability of one or more sites based on detailed site evaluation criteria. Field investigations would include airborne and

surface-based geophysical surveys, characterization of the existing environment, drilling and monitoring of boreholes, field and laboratory testing and monitoring activities.

4.2.1 Site Evaluation Criteria

The draft siting document proposed a set of initial criteria to support initial screenings and a list of more detailed criteria to support feasibility studies and detailed site characterizations. The proposed initial screening criteria include the following:

a) The site must have enough available land of sufficient size to accommodate the surface and underground facilities;

b) This available land must be outside of protected areas, heritage sites, provincial parks and national parks;

c) This available land must not contain groundwater resources at the repository depth, so that the repository site is unlikely to be disturbed by future generations;

d) This available land must not contain economically exploitable natural resources as known today, so that the repository site is unlikely to be disturbed by future generations; and

e) This available land must not be located in areas with known geological and hydrogeological features that would prevent the site from being safe.

The more detailed geoscientific evaluation criteria include a wide range of geoscientific factors that have been organized around the five following safety functions that a site would need to fulfill in order to be considered suitable:

a) The geological, hydrogeological, chemical and mechanical characteristics of the site should: (i) Promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances; (ii) Promote long-term containment of used nuclear fuel within the repository; and (iii) Restrict groundwater movement and retard the movement of any released radioactive material;

b) The containment and isolation functions of the repository should not be unacceptably affected by future geological processes and climate changes;

c) The surface and underground characteristics of the site should be favourable to the safe construction, operation, closure and long-term performance of the repository;

d) The site should not be located in areas where the containment and isolation functions of the repository are likely to be disrupted by future human activities; and

e) The characteristics of the site should be amenable to site characterization and site data interpretation activities.

In 2010, NWMO plans to refine the siting process proposal based on input from Canadians.

4.2.2 Generic Approach for Implementing Initial Technical Site Evaluations

The NWMO is developing, in collaboration with Golder Associates and AECOM, generic plans and approaches for conducting initial screenings and feasibility studies. The plans will describe: how the initial screening and detailed criteria will be applied; the data needs and data sources required to conduct the evaluations; the nature and extent of the preliminary field studies that may be carried out during the feasibility studies; and will propose possible approaches that could be used to assess larger areas versus specific sites.

The outcome of this work program will be used as a basis for discussion with interested communities for developing procedures for site-specific evaluation of geological suitability.

4.2.3 Background Geoscientific Information on the Four Nuclear Provinces

Since 2008, NWMO has been reviewing and compiling available geoscientific information in order to develop a better understanding of the geoscientific characteristics of the four nuclear provinces where the site selection process will be focussed (Saskatchewan, Ontario, Québec and New Brunswick). In 2009 NWMO completed a study to: (1) Review the geology of the four nuclear provinces and the geoscientific factors that need to be considered for siting a DGR; and (2) Assess the feasibility of early exclusion of large geographic areas within the four nuclear provinces that would be unsuitable for safely hosting a DGR (Leech et al., 2009). The geoscientific characteristics and factors considered were grouped under geology, geomechanics, seismicity, hydrogeology, hydrogeochemistry and the potential for economically exploitable natural resources.

The assessment of whether the geoscientific factors considered could be used to exclude large areas of the four nuclear provinces early in the siting process highlighted two main challenges. Firstly, most of the geoscientific factors that need to be considered require site-specific information at depth, which is typically lacking at early stages in the siting process. The second challenge is associated with the large geographic extent of the four nuclear provinces (3,300,000 km^2) compared to the typical repository scale at which site-specific geoscientific information is needed (~6 km^2). The study concluded that it is not practical to exclude large areas of the four nuclear provinces early in the siting process (pre-screening) based on the geoscientific factors identified. However, some of the identified geoscientific factors may be used as exclusion factors at later stages of the site evaluation process as more local scale and site-specific information becomes available.

4.2.4 Review of Borehole Based Site Characterization Methods

Borehole geophysical methods can provide important in situ information for a range of disciplines (including geological, hydrogeological, hydrochemical and geotechnical) that together contribute to the development of a geosphere model for a potential DGR site. For example:

- Borehole geophysical data is essential to developing an understanding of site stratigraphy and rock lithology to support the geological model;

- Important physical properties can be measured using borehole geophysics. For example, sonic and density geophysical data can be used to derive estimates of rock engineering properties;
- Geophysical imaging tools (televiewers and dipmeters) can be used to identify and orient fractures and structures in the rock. This information, together with other data sets, can be used to understand how the fracture network is interconnected; and
- Flow testing tools can be used to estimate hydraulic properties of the rock and evaluate interconnections in the rock system.

In order to develop readiness for the later stages of site evaluation, that will involve intrusive borehole investigation, a report reviewing available borehole-based geophysical tools and techniques for characterizing DGR candidate sites was prepared by Monier-Williams et al. (2009). The report evaluates borehole methods and focuses on state-of-the-science technologies, their applicability, accuracy, limitations and constraints, and best practices. Nine studies were discussed, including both crystalline and sedimentary rock environments, in Europe and North America. The project sites presented include nuclear repository sites, underground research sites and heavy civil works.

The techniques considered include: wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and nuclear magnetic resonance logs); flow logging tools (impeller, heat pulse, electromagnetic, and fluid tracking); seismic methods (sonic and full waveform, tomography, reflection and vertical seismic profile surveys); borehole radar; and borehole time domain electromagnetic surveys and cross-hole electromagnetic surveys. The report provides guidance on the benefits and constraints associated with specific techniques. In addition, typical borehole geophysical applications were reviewed, including the determination of lithology and stratigraphy, physical properties, rock structure, hydrogeologic properties, as well as in situ stress investigations and well inspections.

4.2.5 Seismicity

The seismic design of a DGR 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. 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: (1) Seismic Hazard Assessment for the prediction of the seismic risk and environment at the site; (2) Evaluation of the ground response to ground shaking at depths; and (3) 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 2009, Geoscience seismicity R&D activities continued to focus 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). Supporting activities include understanding attenuation of seismic ground motion with depth, reviewing paleoseismology methods 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 host areas are identified.

4.2.5.1 Seismic Hazard Assessment in Low Seismicity Areas

Canada has an average of 3,500 recorded seismic events per year with the bulk of the activity occurring in the Pacific coast region and the remainder distributed in the Arctic regions, the St. Lawrence River area and along the east coast of Canada. In contrast, the regions of central and most of eastern Canada are located in low seismicity regions of the North American Plate which includes the stable Cratonic Regions. Central and eastern Canada, like the central and eastern United States, has few visible active faults and generally localized seismicity. The seismic stability of these regions in Canada makes them attractive for the siting of long-term nuclear waste management facilities. It is therefore important to develop reliable methods to estimate the long-term seismic hazard associated with these stable regions.

In 2009, NWMO initiated a state-of-the-science review of existing seismic hazard assessment approaches for low seismicity regions. The review is on-going and will evaluate the validity of the underlying assumptions associated with seismic approaches in SCRs and will attempt to identify the different physical processes of stress-strain regimes and related release mechanisms that characterize or dominate active verses stable continental regions.

4.2.5.2 Seismic Monitoring of the Canadian Shield

NWMO continues to support seismic monitoring activities conducted by the Canadian Hazards Information Service (CHIS) of the Geological Survey of Canada (GSC) in low seismicity areas of the northern Ontario and eastern Manitoba portions of the Canadian Shield. CHIS maintained a network of twenty-six seismograph stations in 2008. A total of 114 seismic events were recorded in this period (Figure 4.1a). The two largest events were located in the Atikokan and the Cochrane-Kapuskasing regions of Ontario. The Nutti magnitudes (m_N) recorded were 3.2 and 3.0, respectively. The Atikokan event was the first recorded event above m_N 3.0 in this region. The magnitude-recurrence curves shown in Figure 4.1b were revised to incorporate the events recorded in 2008. The monitoring results are summarized in Hayek et al. (2009).

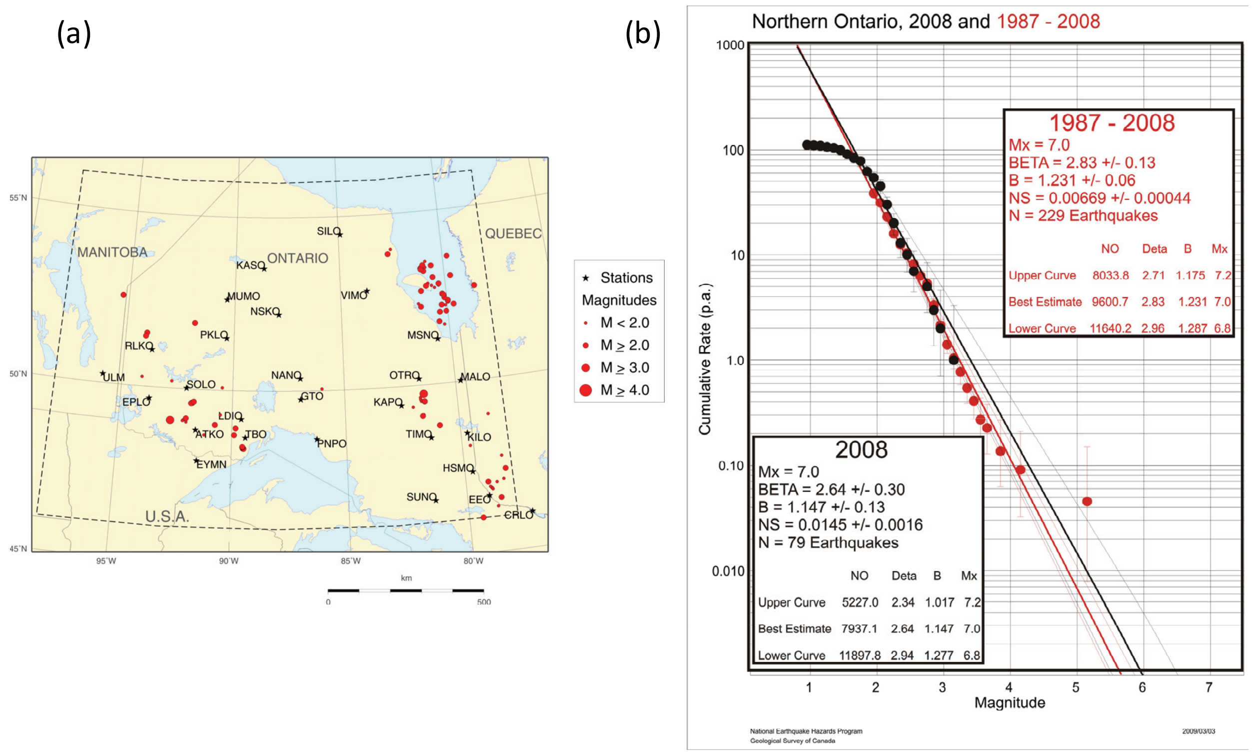

Figure 4.1: (a) 2008 Seismic events in Northern Ontario and adjacent areas. (b) Recurrence curves for Northern Ontario. From Hayek et al. (2009).

4.2.5.3 Seismic Response of Underground Facility – Sudbury Neutrino Observatory

Seismic monitoring using five surface and underground seismograph stations continued for the final year (2007 - 2009) for the POLARIS Underground Project (PUPS) at the Sudbury Neutrino Observatory (SNO) (Figure 4.2). The main objective of PUPS is to investigate the host rock response at repository depths under seismic ground motions. From case histories, it is known 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). The PUPS POLARIS experiment quantifies the amount of seismic ground motion reduction at various depths, known as surface effect (Atkinson and Kraeva, 2010). The results from the third and final year in the study are presented in Atkinson and Kraeva (2009).

The PUPS project has analyzed ground motions on the surface and underground for 106 local events (shallow mining-induced events and blasts), 66 regional earthquakes (moderate events hundreds of km away), and 73 teleseismic events (large earthquakes >1000 km away). The analyses have led to several important conclusions regarding the differences between earthquake ground motions recorded on the surface and those recorded in underground cavities. In general, earthquake ground motions underground are lower in amplitude than those on the surface. The relationship between underground and surface motions is complex, with the ratio of surface/underground motions being a frequency-dependent function that depends on the type of earthquake and the depth of the underground cavern (Figure 4.3). Motions on the surface are amplified in specific frequency ranges due to the presence of surface waves in the signal. For earthquakes at shallow depths, occurring nearby, there are strong surface waves that cause a peak amplification of surface motions (near a frequency of 2 Hz) relative to those underground, often exceeding a factor of two. For larger earthquakes happening further away, the surface waves cause amplification at longer periods. These motions decrease in amplitude as the depth of the underground station increases, because surface-wave amplitudes die off with increasing depth. At very low frequencies (0.1 Hz) and at very high frequencies (>10 Hz), underground and surface motions are very similar in amplitudes. In general, the potential for surface waves and the frequency range that they affect is dependent on the characteristics of the source (such as its depth) and the distance to the site. These factors should be considered when assessing the seismic hazard for underground repositories and may be used to reduce the predicted ground motion levels for specific types of events.

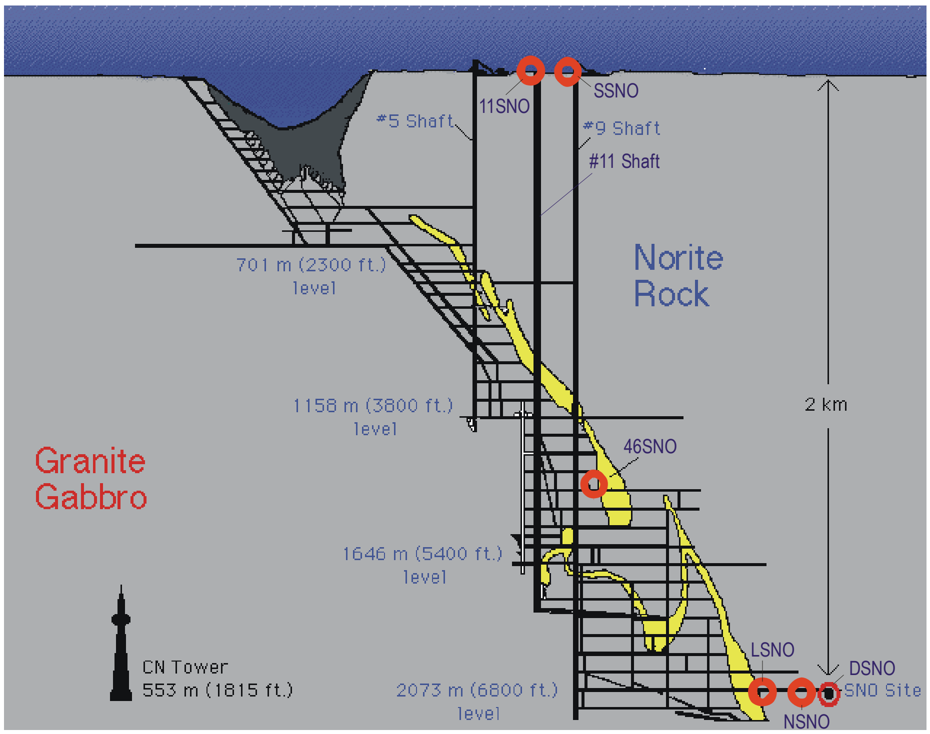

Figure 4.2: SNO Lab and seismograph station locations (SE-NW direction). Approximate positions of stations are shown by the red circles.

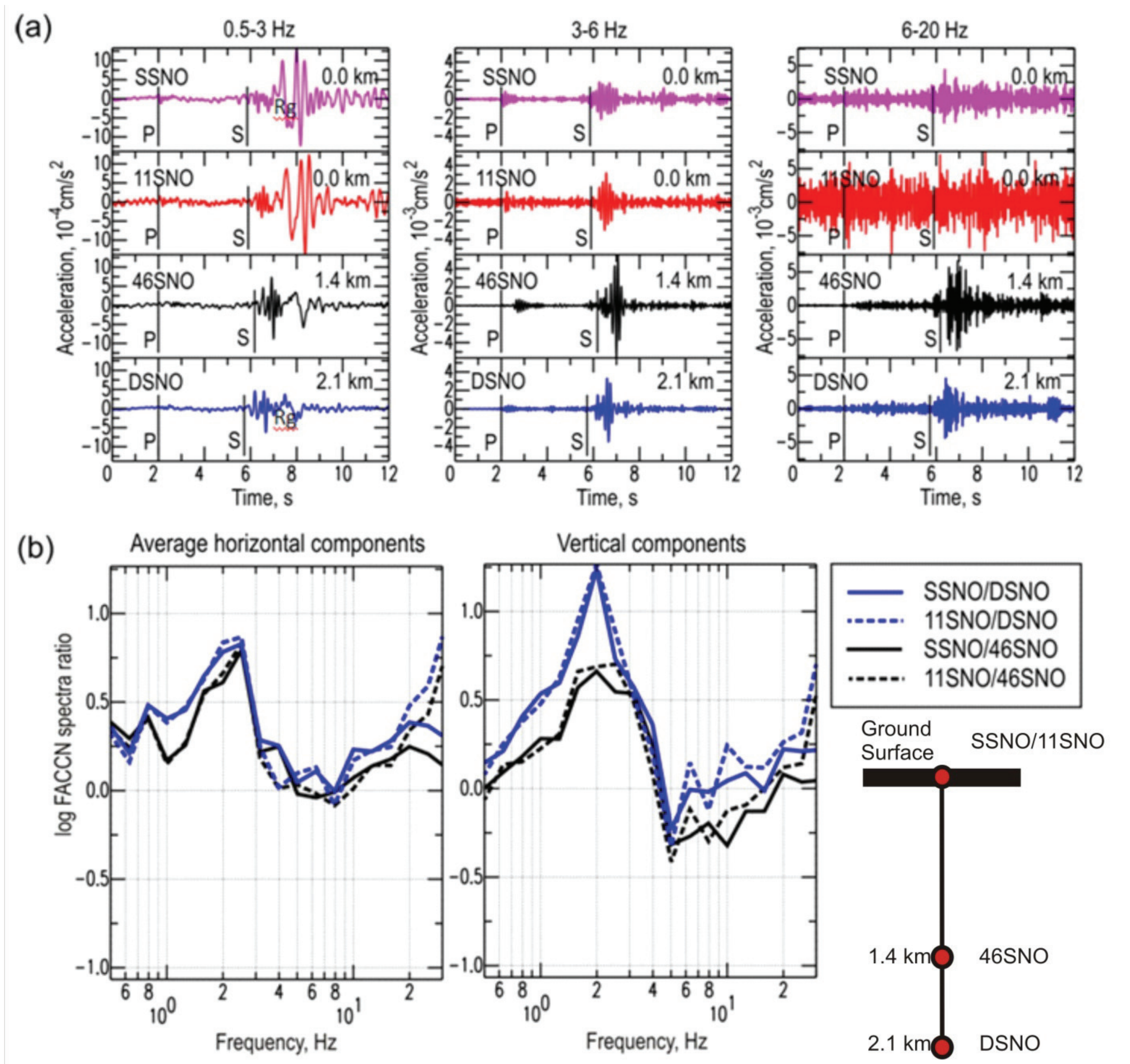

Figure 4.3:The MN2.1 08/05/2008 mining event 35.3 km from the SNO Lab. (a) Frequency-amplitude variability depending on the station depth. Vertical components of ground motion acceleration are shown in three frequency bands, 0.2-4 Hz (left column), 4-9 Hz (central column) and 9-20 Hz (right column). The station names and their depths are given above the traces. (b) Log ratios of surface stations to underground stations calculated for Fourier spectra of average horizontal component (left) and vertical component (right) of S-waves. From Atkinson and Kraeva (2009).

4.2.5.4 Paleoseismology

Paleoseismology is the interpretation of past seismic events using sedimentary deposits formed after fault ruptures or those disturbed by ground shaking. Paleoseismology, as an interdisciplinary field of research, utilizes concepts from Quaternary geology together with seismology, structural geology and tectonics to enhance our knowledge of past seismicity in an area. The primary focus of paleoseismology is its effects on Quaternary age deposits and landforms. In Canada, quaternary deposits form most of the overburden and have profoundly altered its geomorphology. Most of the glacial sediments in Canada were deposited during the Late Wisconsinan when the Laurentide ice sheet reached its maximum about 20,000 years ago. Any detectable features of paleoseismic disturbance that may have occurred in these sediments during and after this period will enhance the existing knowledge for supporting the assessment of regional seismic risk. A state-of-the-science review was conducted by John Sims & Associates on the applicability of paleoseismology methods to the geological settings typical of the Four Nuclear Provinces (Saskatchewan, Ontario, Québec, and New Brunswick) to assess whether traditional seismic hazard assessment methods could be complemented by paleoseismology studies.

The review presents an update of methods and material published in J.P. McCalpin's book "Paleoseismology" in 1996 and assesses their applicability to typical central and eastern Canadian sedimentary and crystalline rocks for the purpose of siting and designing a DGR. The review includes an overview of paleoseismological concepts and technique (Figure 4.4), a review of recent advances in paleoseismology and a brief review of the geological and seismological settings of the Four Nuclear Provinces, with particular emphasis on Quaternary sedimentary deposits. The review also examines the use of geological features such as liquefiable sediments, paleolacustrine deposits, and submarine sedimentary structures in modern lakes, speleothems and surface travertine, precarious rocks and surface post glacial faulting to extract seismological information and extend the seismic record. It was concluded after compiling and reviewing geological and seismological literature and maps for all four provinces that reconnaissance of seismic induced deformation in paleolactrine varved deposits and liquefaction features in river and stream banks could provide opportunities for gathering additional information on past unknown moderate to large earthquake shakings. The results will be published in a peer-reviewed report in 2010.

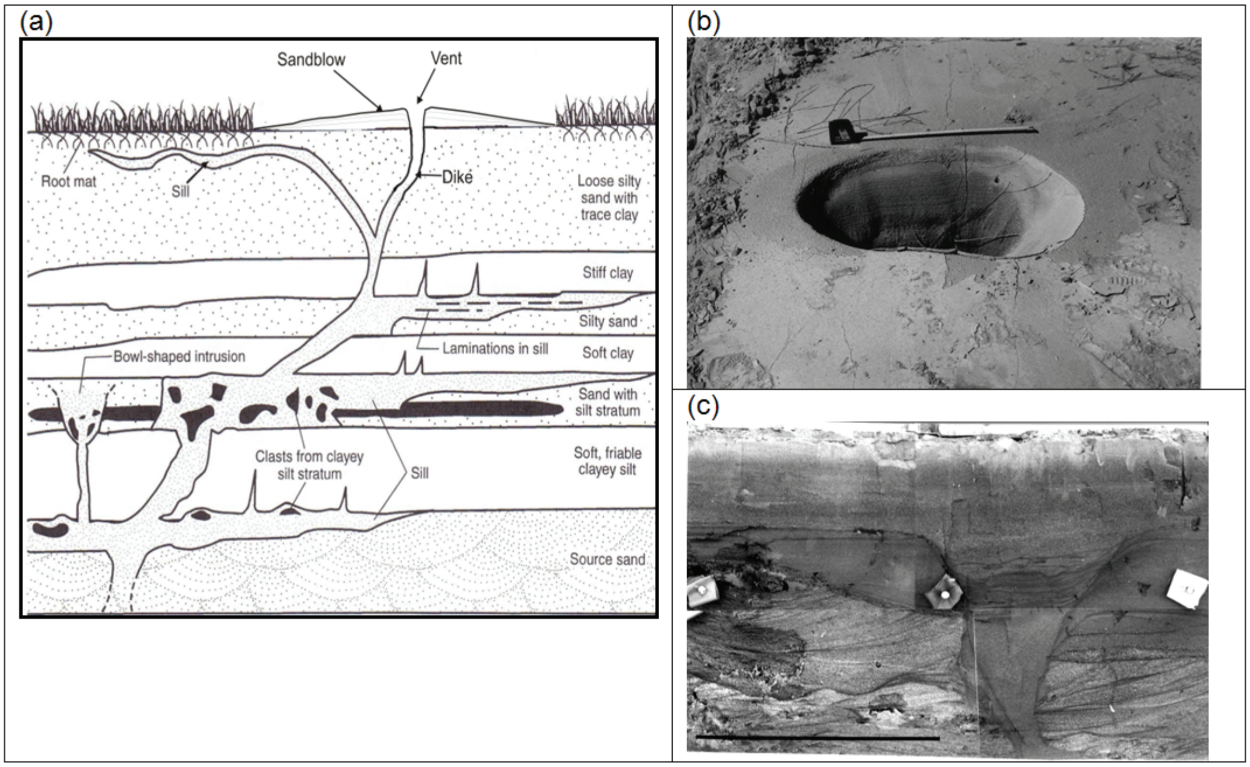

Figure 4.4: (a) Schematic section showing the relationship of various structures associated with paleoliquefaction. Not all structures are seen in every outcrop. Modified from Obermeier and Pond, (1999). (b) View of a sand blow cone and vent formed at Soda Lake, CA during the 1989 Loma Prieta earthquake. From Sims and Garvin, (1995). (c) Section view of sandblow and sand dike from same earthquake showing internal structure of cone deposits. Scale bar at lower left is 10 cm. From Sims and Garvin, (1995).

4.2.6 Matrix Porewater Characterization in Sedimentary Rock

Chemical and stable isotopic ($\delta^{18}O$, $\delta^{2}H$) compositions of groundwaters and matrix porewaters provide information on the origin and evolution of the groundwater flow system and can be used to determine groundwater fate over geologic time frames. In addition, near-field performance, safety assessment and groundwater transport/evolution models require knowledge of groundwater geochemical compositions. The composition of water within the rock matrix (matrix porewaters) of crystalline and sedimentary formations may have compositions similar to those of the groundwaters. However, direct information on porewater composition is required in order to support this hypothesis.

Methods to extract matrix porewaters include: vacuum distillation; out-diffusion of pore fluids into deionized water; crush and leach; diffusive exchange and ultracentrifugation of broken rock pieces. Each of these techniques has its own benefits and limitations which are dependent on the properties of the rock sample. In particular, extraction of porewater from low-permeability sedimentary rocks with low water content can be challenging and there are few direct methods available for the extraction of pore fluids these rock types. As such, in 2009, NWMO continued to explore the applicability of the ultracentrifugation and diffusive exchange techniques for extraction of porewater from low permeability sedimentary rocks.

4.2.6.1 Ultracentrifugation

A collaborative work program was undertaken in 2005 with Gascoyne GeoProjects and the U.S. Geological Survey to develop a protocol using core samples to determine the elemental and isotopic compositions of porewaters in deep crystalline environments. 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, which involves centrifuging broken core at 15,000 rpm under controlled temperature and pressure, showed particular potential for rapidly and directly extracting porewater for chemical and isotopic measurements (results summarized in Gascoyne and Hobbs, 2009). As such, in 2007, work began to further 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 a freshly-drilled limestone core from Bowmanville, Ontario. Results from this study demonstrated that it was possible to extract small quantities (<0.5 ml) of porewater from the low porosity limestone samples (Gascoyne and Hobbs, 2009). However, the chemical compositions and salinity of the extracted porewater were found to vary with subsequent extractions on the same core sample. It was suggested that this variability was either the result of natural variability in the samples or a result of changes induced by sample handling and experimental procedures.

In 2008, a two-year work program began to investigate the variability observed in the previous study (Gascoyne and Hobbs, 2009) and to further develop the ultra high speed centrifugation technique for the determination of matrix porewater compositions in sedimentary rocks. Experimental results to date indicate that the ultracentrifugation technique may not be able to extract matrix porewater from very low porosity samples, however preliminary results show good reproducibility between replicate analyses of moderate porosity sedimentary rocks. In addition, good reproducibility was observed during successive extractions from the same limestone core sample (Figure 4.5).

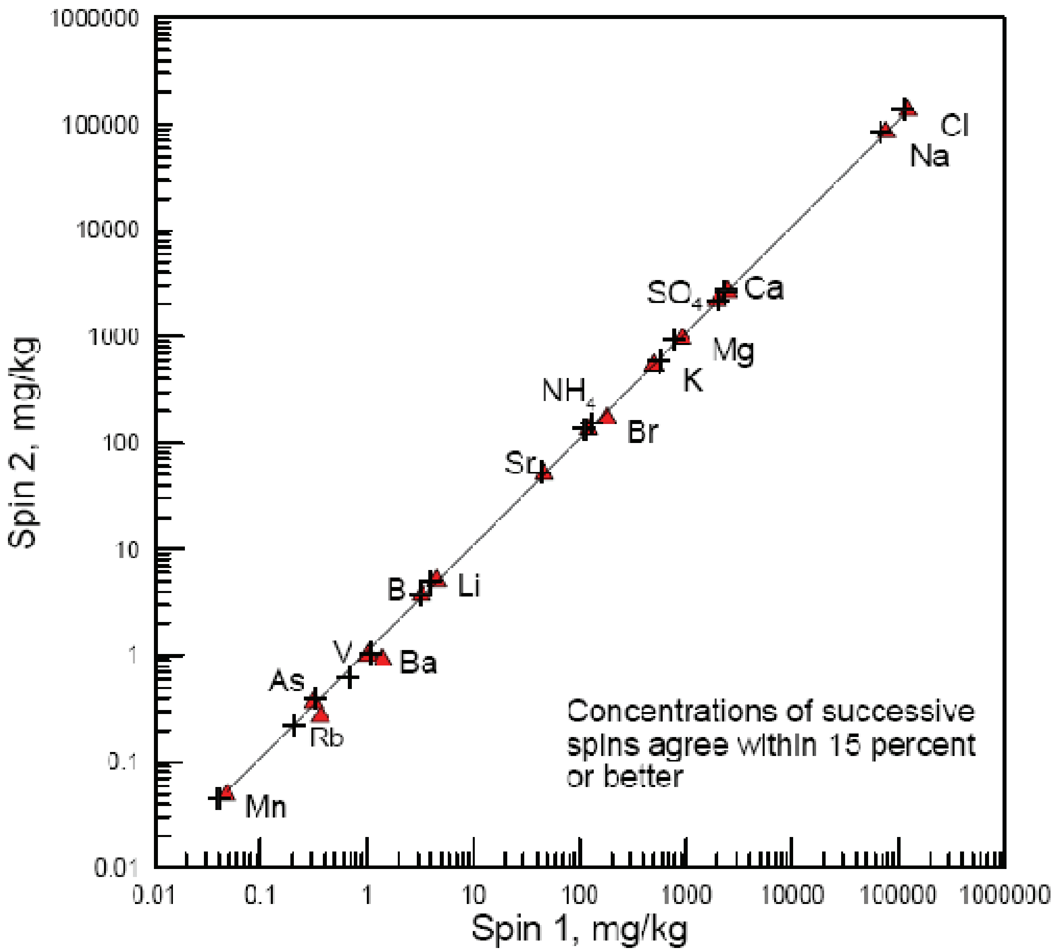

Figure 4.5: Comparison of the dissolved ion and elemental composition of water extracted by successive spins of two limestone samples.

4.2.6.2 Diffusive Exchange in Sedimentary Rocks with High Salinity Porewater

In 2009, a two-year work program was initiated in collaboration with the University of Bern, Switzerland, to evaluate and benchmark a newly adapted diffusive exchange technique for measuring stable isotope compositions of saline matrix porewaters. Testing of this technique will focus on highly saline Na-Ca-Cl or Ca-Na-Cl type porewaters, such as those found in Canadian crystalline and sedimentary rocks. The main objectives of the on-going work program are to: (1) Conduct testing to evaluate and benchmark the adapted diffusive exchange technique and determine its applicability to rocks with a range of different mineralogies, porosities and porewater salinities; and (2) Improve our ability to constrain anion-accessible porosities in rocks containing highly saline porewaters. This information is important for the interpretation and modeling of porewater evolution – for example, from natural tracer profiles collected across sedimentary sequences.

4.2.7 Assessment of Radionuclide Transport Processes

4.2.7.1 Diffusion in Sedimentary Rock

Within low permeability geological formations, diffusion is expected to be the dominant solute transport mechanism. To assess the ability of the geosphere to contain and isolate used nuclear fuel in a DGR over the relevant time frames (>100,000 years), there is a particular importance in understanding the diffusive transport properties of sedimentary and crystalline rocks. 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 and require experimental times of several weeks to months. 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).

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 to study diffusive transport and evolving reactivity in sedimentary rock (sandstone, limestone and shale). 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. Because time-dependent diffusion profiles are measured, radiography allows estimates of the diffusion coefficient within a sample before steady-state is reached, resulting in substantially shorter measurement times (days to weeks) in comparison to through-diffusion techniques (weeks to months). A comparison of the through-diffusion and 1-D X-ray radiography technique was completed in 2008, 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., 2009a, b). Similar values for the effective diffusion coefficient (De) were determined using the radiography and through-diffusion methods. In 2009, a study of rock diffusion properties across a sedimentary sequence underlying southwestern Ontario was completed, investigating the variations in diffusion properties with changes in lithology. The potential for up-scaling up of laboratory diffusion measurements to estimate diffusion coefficients on the formation scale was investigated. A new radiography technique was also developed to quantify diffusion-reaction processes using a non-conservative tracer, cesium (Figure 4.6).

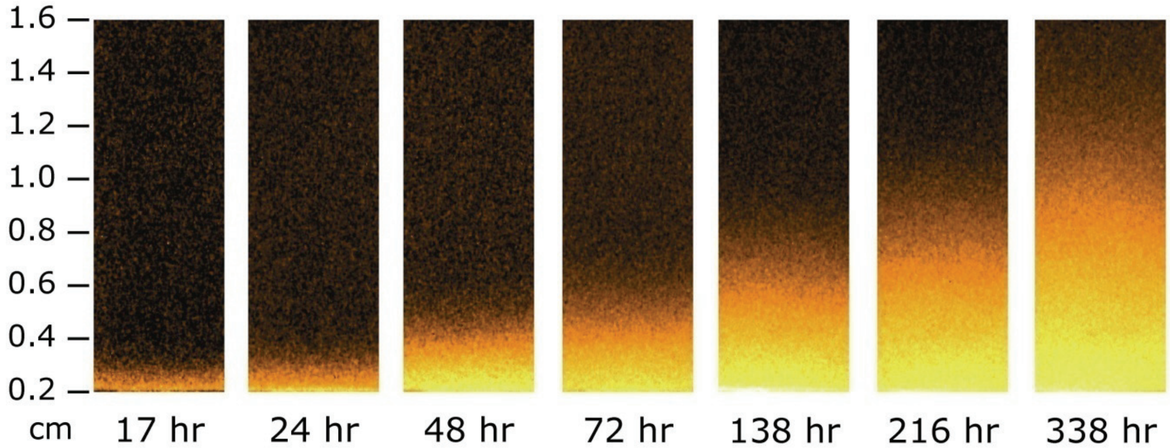

Figure 4.6: Colourized time series images illustrating the transport of Cs through a rock sample.

4.2.7.2 Scale-Dependency of Diffusion

Diffusion is an important mechanism for solute transport in low permeability rocks. The matrix diffusion coefficient is a key parameter describing both the diffusion process in the rock matrix and diffusive mass transfer between fractures and the rock matrix. 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 DGR.

In 2009, a preliminary literature review was conducted to evaluate the diffusive processes that may occur in rock formations. In particular, diffusion processes in heterogeneous sedimentary and crystalline rock with microcrack networks (i.e. cracks at the microscopic level) were examined. Experimental approaches for determining diffusion coefficients were also reviewed, and a preliminary compilation of effective diffusion coefficient values measured in both laboratory and field-scale tracer tests, for a variety of rock types, was prepared.

The preliminary compilation of measured diffusion coefficients at the laboratory and field scale suggests that, as expected, matrix diffusion is likely scale-dependent. The review indicated that as the scale increases (e.g. from laboratory to field scale), changes in the effective diffusion coefficient may occur due to heterogeneity in the aperture size of the microcracks, size of the matrix (rock) block, the density of the microcracks in the network, the connectivity between the microcracks, and the sorption capacity of the microcrack walls. These preliminary results suggest that further understanding of the impact of scale on diffusion processes is needed to determine the relationship between laboratory-determined diffusion coefficients and in situ, field-scale diffusion. NWMO intends to apply the results of the review to future work programs comparing diffusion coefficients measured at the laboratory-scale to diffusion coefficients measured at the field-scale for the same geological formation.

4.2.7.3 Sorption Properties of Sedimentary Rock under Saline Conditions

Sorption plays an important role in regulating the migration of radionuclides in the geosphere. A state-of-the-science review was conducted 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 engineered barrier systems, scientific literature on sorption in saline waters, as well as theoretical considerations of sorption processes under saline conditions. The report concluded that sorption properties of rocks in general are fairly well understood and made recommendations for improving the understanding of sorption under highly saline conditions. These recommendations proposed a path forward for an experimental program to quantify sorption in saline waters within the Canadian used fuel program and suggested further development and testing of experimental protocols. On the basis of these recommendations, a two-year experimental program on sorption in sedimentary rocks under high salinities was initiated in 2009 which will develop a quantitative understanding of the impact of high TDS (up to ~300 g/L) on sorption and evaluate the effect of groundwater Na/Ca concentration ratios on sorption processes. Transport experiments in rock cores will also be conducted to investigate the role of sorption in mass transport of brine solutions of various compositions. Surface complexation modeling will then be applied to evaluate sorption mechanisms. This will provide insight on the role of sorption in radionuclide migration in saline waters and how it should be considered in safety assessment scenarios.

4.2.8 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 2009, the main focus of the work program was to build on the initial development of the NWMO's GeoSystem consisting of web-enabled geospatial data catalogue and mapping tools. Particular focus was placed on expanding and quality assuring the NWMO Geospatial Data Repository and optimizing functionalities of the existing software tools. The overall objective in 2009 was to further improve the capability for NWMO staff to explore and interact with relevant geospatial data sets covering national and nuclear-province scales.

4.2.9 Fracture Network Modelling

In crystalline shield environments, the presence and distributions of fractures are one of the most important factors affecting the flow system surrounding a potential repository. The ability to accurately represent the spatial distribution and connections of fractures will increase the fidelity of local and regional scale groundwater models. Activities in 2009 focused on refining and documenting a version of the FXSIM3D software application to facilitate technology transfer to other users within the geoscience and geological engineering communities.

FXSIM3D is a research software application that was developed under Ontario Power Generation's DGR 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 (Srivastava 2002a,b; Srivastava and Frykman, 2006). The types of data acceptable for the FNM code are:

- Surface expressions of fractures;
- Statistics on fracture density;
- Structural geology principles that govern down-dip behaviour; and
- Truncations rules for when lineaments intersect.

The family of FNMs produced by this method are probabilistic in that they consist of equally-likely renditions of fracture geometry. The FNM generated are 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 (Figure 4.7). Such models are useful as input to many types of subsequent analyses, from mechanical stability to groundwater flow and contaminant transport and are also well suited for studying issues involving risk assessment and quantification of uncertainty. Additionally, this methodology for creating FNMs is useful at all stages of site characterization as it can provide a framework for guiding field investigation activities with the objective of reducing the inherent uncertainty in conceptual geosphere models of fractured rock, thereby improving the overall safety case for a DGR.

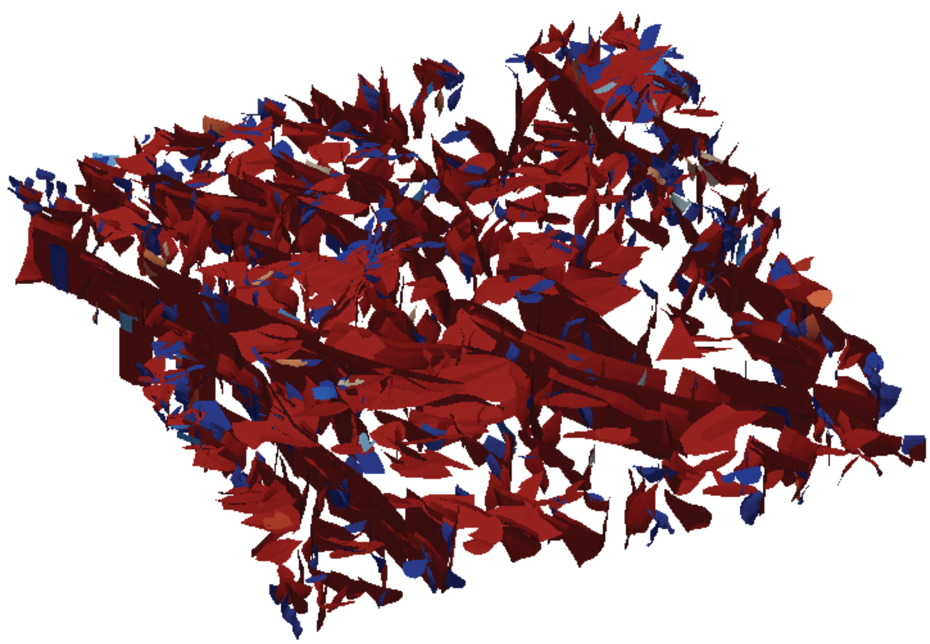

Figure 4.7: Example of a Fracture Network Model generated using FXSIM3D software.

4.2.10 Thermo-hydro-mechanical properties of Canadian sedimentary rocks

In 2009, NWMO initiated a two-year work program to investigate the thermo-hydro-mechanical (THM) properties of Canadian sedimentary rocks with the Rock Fracture Dynamics Facility (RFDF) at the University of Toronto. The objectives of the work program are to: (1) Document the state of knowledge related to the role of the near-field thermal, hydraulic and mechanical (THM) processes in the design and performance of a DGR for used nuclear fuel; (2) Test thermal properties of sedimentary rocks that are representative of those found in Canadian deep sedimentary basins; and (3) Develop and maintain Canadian expertise in the areas of THM experimental procedures.

A literature review of the THM properties of sedimentary rocks will be completed in early 2010 and will serve as a basis for developing an experimental program to investigate individual thermal (T), hydraulic (H) and mechanical (M) effects, as well as the coupled effects of TH, TM, HM, and at a later stage, fully coupled THM processes. The polyaxial experimental setup is shown in Figure 4.8.

(a) (b)

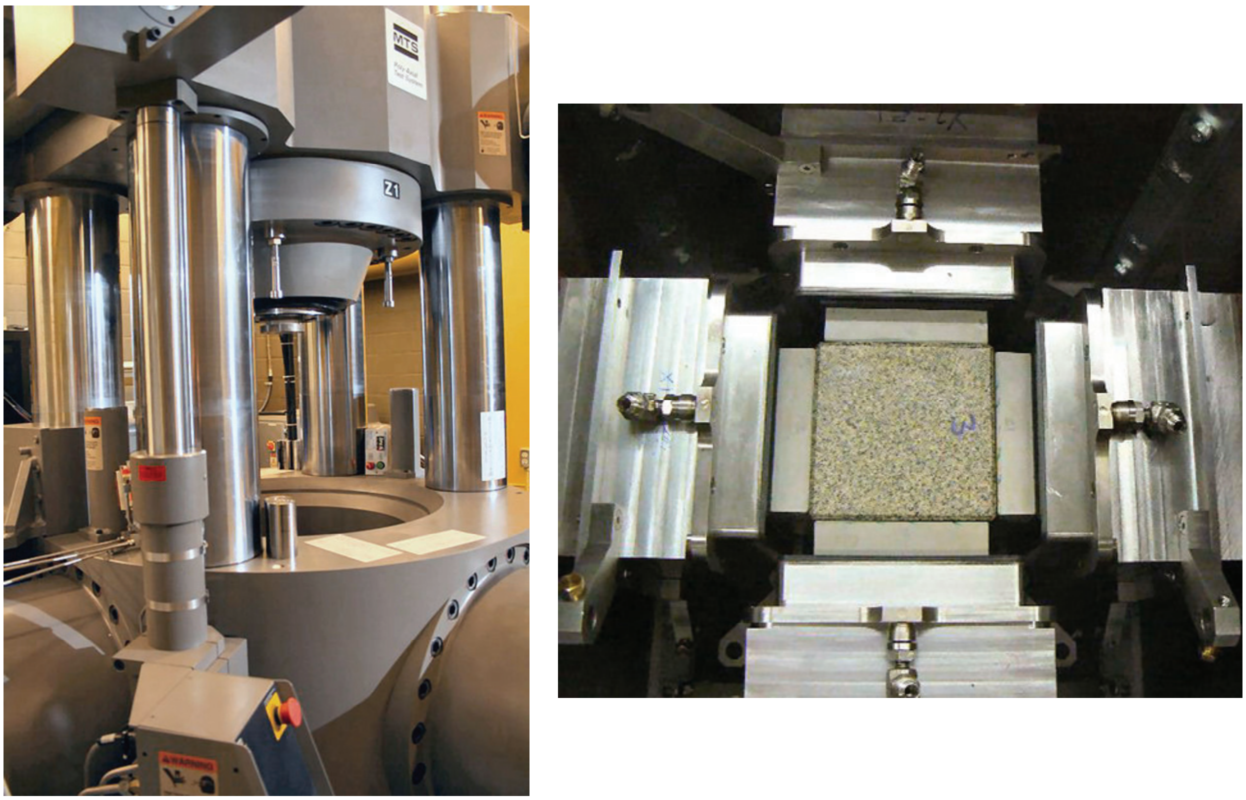

Figure 4.8: THM experimental equipment at the Rock Fracture Dynamics Facility, University of Toronto. (a) Custom-made polyaxial loading machine (MTS Systems Corporation). (b) Polyaxial geophysical imaging cell which provides real-time geophysical monitoring during coupled THM experiments.

4.2.11 Excavation Damage Zone in Sedimentary Rock

The Excavation Damage Zone (EDZ) around underground openings is an important factor that needs to be considered for the development and assessment of a DGR. Excavation of the DGR will induce damage in the rock mass surrounding cavern or shaft openings which will be dependent on the excavation method, the potential for fracturing to occur and the properties of the rock mass and stress field. A study was initiated by NWMO in 2009 to review the state-of-the-art in predicting the extent and key material parameters associated with the EDZ around bored and blasted tunnels in sedimentary rocks, primarily carbonates and clay-shales.

Two objectives of the review were to examine the ability of numerical models to: (1) Simulate the evolution of the EDZ under different excavation sequences; and (2) Determine the required extent of shaft cut-off and seal applications. For example, Figure 4.9 shows the cut-off scheme design proposed by ANDRA to interrupt the continuity of the damaged zone. The study also investigated the use of different stress and strain indicators to delineate numerically different damage zones around an excavation opening, such as the Excavation Disturbed Zone (EdZ), Excavation Damage Zone (EDZ) and High Damage Zone (HDZ) (Tsang et al., 2004) from stress analysis (e.g. Figure 4.10). The review will be completed in early 2010 and will form the basis for future NWMO studies evaluating the EDZ in Canadian sedimentary rocks.

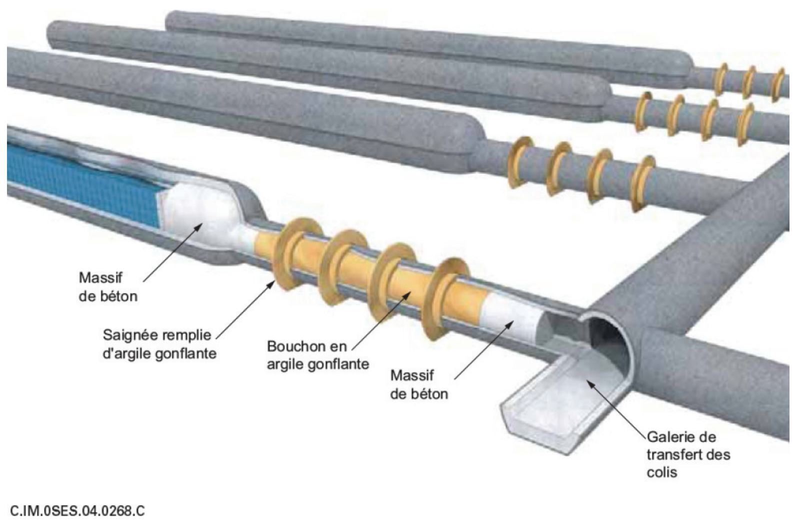

Figure 4.9: EDZ cut-off in ANDRA's repository concept. From ANDRA (2005).

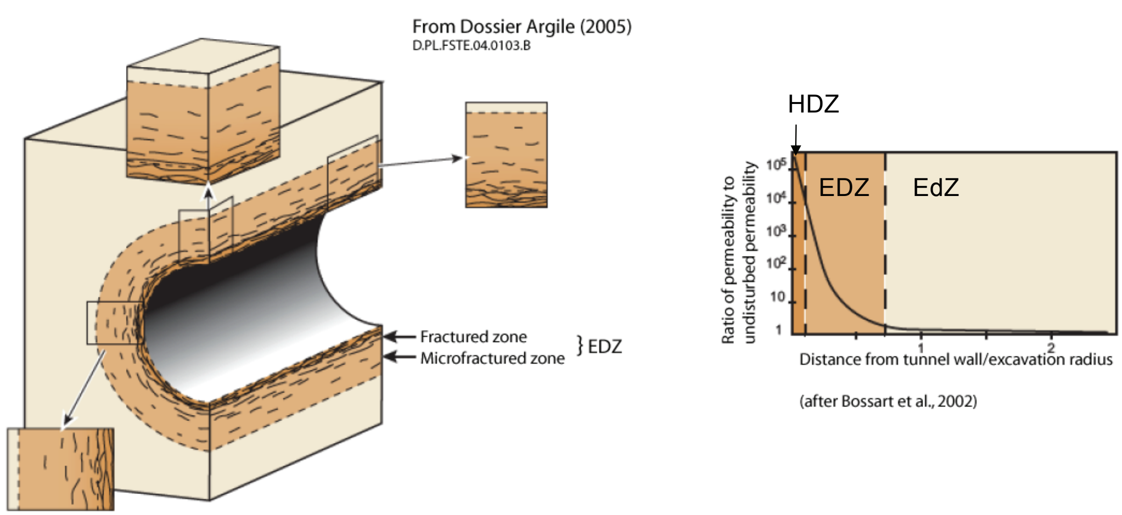

Figure 4.10: Schematic illustrating definitions of EdZ, EDZ and HDZ for an unjointed rock. From ANDRA (2005).

4.2.12 Mont Terri Project

In 2009, NWMO continued its participation as a partner in the Mont Terri Project. The main goals of the collaborative research project are to: (1) Test and improve techniques for hydrogeological, geochemical and geotechnical investigations in an argillaceous formation; (2) Characterize the Opalinus Clay and its behaviour; and (3) Explore the interactions between the Opalinus Clay and other materials. In order to facilitate these goals, a series of experiments are being conducted in boreholes up to 30 m long, drilled in different directions. The Mont Terri project consists of a series of individual experiments and involves collaboration of international organizations such as NWMO, ANDRA, NAGRA, BGR, CRIEPI, ENRESA, GRS, HSK, IRSN, JAEA, OBAYASHI, SCK-CEN and SWISSTOPO. 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 4.11).

Representatives from the NWMO attended technical meeting 27 (TM-27) in February 2009. The purpose of TM-27 was to plan new and continuing research activities for Phase 15 of the project. One of the new research activities that was initiated in 2009 and to which the NWMO became a contributing member was the disturbances, diffusion and retention project (DR-A). The goal of the DR-A experiment is to use a disturbed system to validate diffusion models of the Opalinus clay. A thorough assessment of the matrix and undisturbed geological system commenced in 2009 in support of DR-A. NWMO also continued to support the long-term monitoring of pore pressure (LP) project in 2009 for which progress in data acquisition via remote data loggers, data synthesis and reporting occurred. Additional details on the project and published reports can be found at the Mont Terri Project website (http://www.mont-terri.ch/).

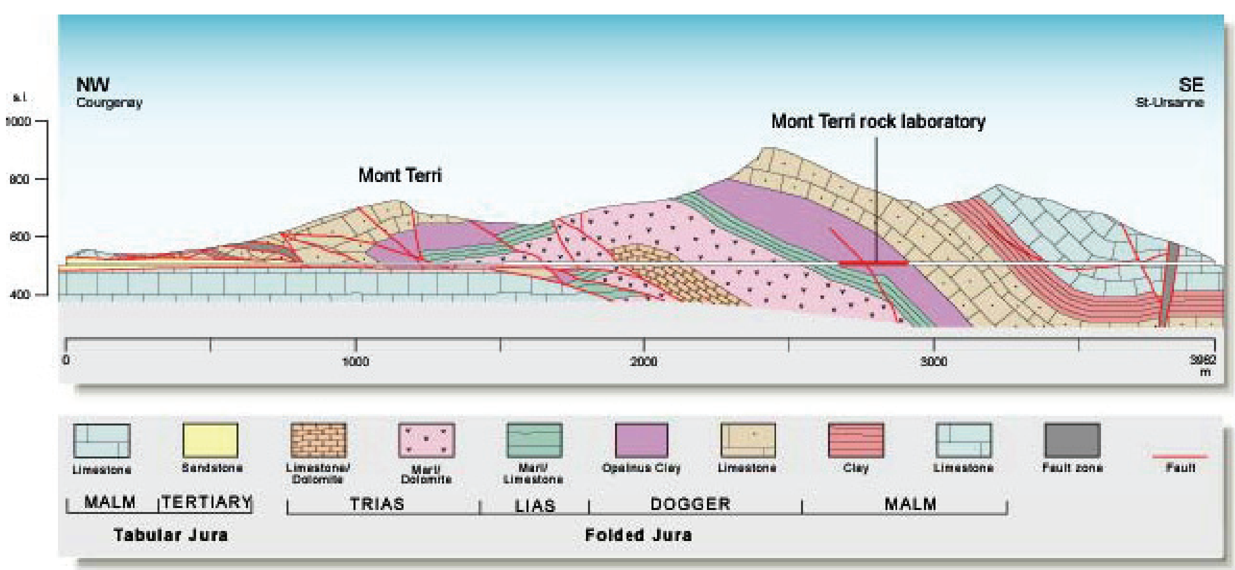

Figure 4.11: Geological cross-section through the Mont Terri anticline indicating the location of the Mont Terri Rock Laboratory. From Hugi et al. (2007).

4.3 LONG-TERM GEOSPHERE STABILITY

NWMO continues to have an active program looking at the long-term stability of the geosphere and its resilience to external perturbations in both crystalline and sedimentary settings. Multidisciplinary activities are being directed to improve the understanding of the signatures and impact of past and future glaciation cycles at repository depths. 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 glaciations 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.

An overview of the main activities is 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 and 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, 2008). The University of Toronto GSM is a state-of-the-art model of continental scale ice-sheet evolution that 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.

There are several aspects of the GSM that require further development to improve predictions of glaciation boundary conditions and consequently improve the overall assessment of a DGR safety case. One of these is the implementation of higher degree physics in the way that the flow of ice over the landscape is described. This includes the consideration of longitudinal stresses and the interaction of ice streams with the ocean. To facilitate the interaction of glacial ice sheet models with coupled climate models, researchers at the University of Toronto are enhancing the GSM to include unstructured grids. Using unstructured grids allows a finer discretization along the boundaries of the ice sheet model, where the glacial ice streams interact with the ocean. An example of basal topography using an unstructured grid is presented in Figure 4.12.

This work program is in the form of a 3-year research grant (2008-2011) to Dr. Peltier's research group at the University of Toronto. The objectives of the program are to: (1) Maintain and further develop modelling capabilities in the area of Glacial Systems Modelling; (2) Maintain and expand Canadian expertise in this area; and (3) Promote knowledge transfer through the involvement of Postdoctoral candidates and graduate students. In addition, NWMO and NSERC jointly awarded an Industrial Postgraduate Scholarship to University of Toronto Ph.D. candidate Heather Andres in support of her climate change research.

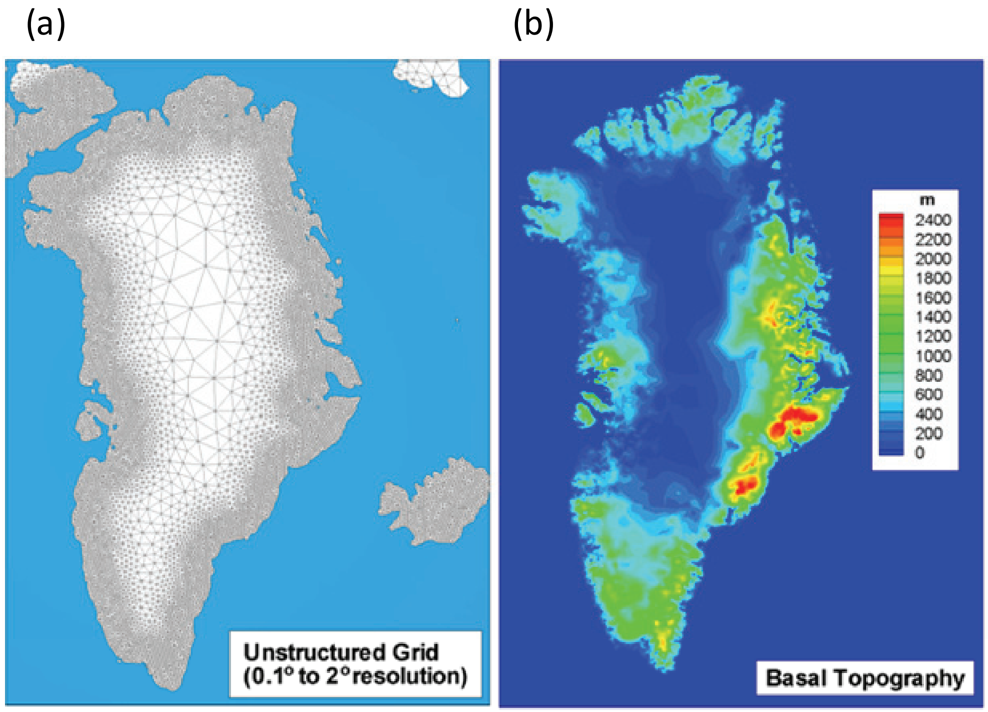

Figure 4.12: (a) Unstructured grid for Greenland Ice Sheet. (b) Basal topography.

4.3.2 Reactive Transport Modelling and Glaciation

Glaciation has been identified as the most plausible and intense perturbation associated with long-term climate change in northern latitudes. An understanding of the impact of glaciation and deglaciation cycles on groundwater at depth is needed to assess the long-term performance of a DGR for used nuclear fuel. Reactive transport modelling is one potential approach for assessing the geochemical and redox stability of these flow systems at depth.

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 had previously not been used to assess glaciation processes in sedimentary rocks. It was however noted that modelling studies of seawater ingress and CO_2 sequestration in sedimentary rocks showed promising results, suggesting that modelling of the geochemical evolution in a 2D-subsection of a sedimentary basin is a realistic goal. Building upon previous NWMO supported work assessing meltwater penetration in fractured crystalline rock using MIN3P reactive transport modelling (Spiessl et al., 2009), work commenced in 2009 to refine the capabilities of MIN3P to model transport in sedimentary rocks. Further details and a summary of the governing equations of the MIN3P multicomponent flow and reactive transport code can be found in Mayer and MacQuarrie (2010).

In 2009, a version of the code that allows for the coupling between density dependent flow and reactive transport (MIN3P-DENS) was developed for simulations on the basin scale, and specific formulations for activity coefficients and ionic strength effects were included into MIN3P-DENS (Pitzer equations). The capabilities and limitations of the modified code for simulating regional scale flow and reactive transport in sedimentary basins were evaluated. Reactive transport modeling will be conducted to assess the evolution of fresh water during glacial recharge for larger scale aquifer-aquitard systems in sedimentary basins, where the sedimentary units dip gently inwards from the basin margins (Figure 4.13). Various scenarios representing groundwater flow and reactive transport in sedimentary basins affected by glaciation/deglaciation events will be simulated.

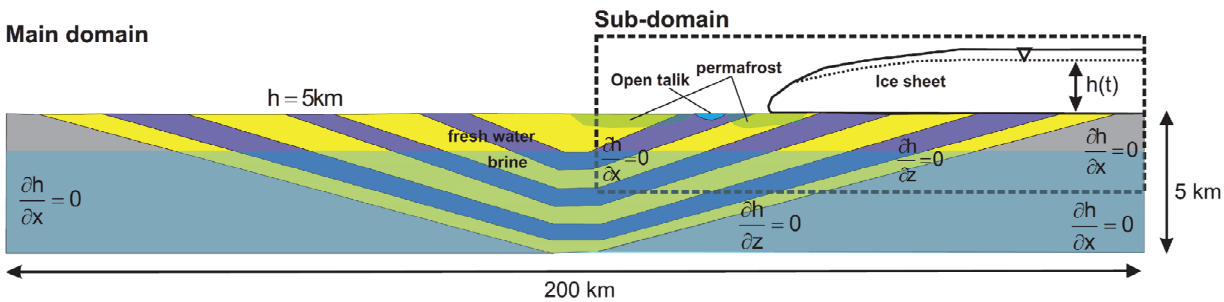

Figure 4.13: Regional conceptual model and potential sub-domain to be used for detailed reactive transport simulations (not to scale, vertical exaggeration approximately 5:1).

4.3.3 Impact of Glaciation on Sedimentary Formations

At the end of 2009, a state-of-knowledge review of glaciation impacts on sedimentary rock formations was completed to assess the resilience of deep groundwater flow systems to physical and chemical perturbations at depths and over timeframes of relevance to a DGR. The state-of-knowledge review was lead by Dr. Mark Person of New Mexico Institute of Mining and Technology.

The review synthesized and critically evaluated field, laboratory, numerical modelling, and theoretical studies of the effects of continental glaciation on subsurface fluid flow and transport, erosion, and deformation in sedimentary basins in the Northern Hemisphere (Figure 4.14) and Antarctica. The review documented the current state of knowledge, identified gaps in that knowledge, and identified areas of uncertainty or controversy. Relevant petrophysical, thermal and mass transport parameters needed to represent subsurface transport processes at the sedimentary basin scale were compiled.

An attempt was made to bracket the possible range of impacts that glaciation events may have had on a series of transport processes, deformation processes and erosion. The levels of uncertainty associated with these estimated impacts were discussed. Special emphasis was placed on processes and issues relevant to nuclear waste isolation in regions that may experience future glaciation and directions for potential future research were outlined.

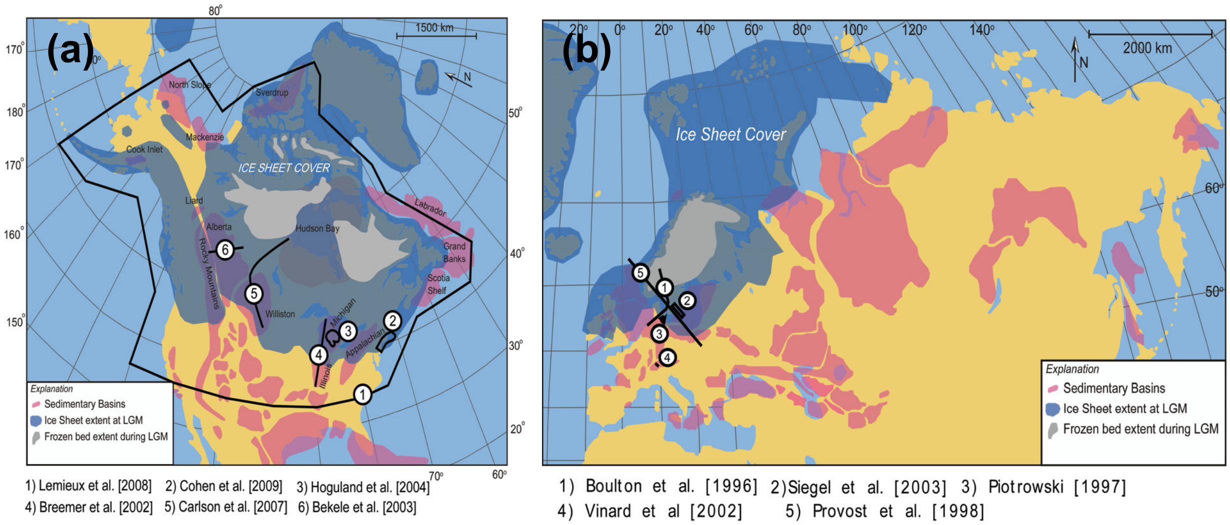

Figure 4.14: Distribution of ice cover (dark gray), sedimentary basins (red), maximum permafrost extent (black line) and locations where the ice sheet had a frozen bed (light gray) during the last glacial maximum across (a) Northern America and (b) Europe. Modified from Denton and Hughes (1981) and Pewe, (1983).

4.3.4 Glacially Induced Seismicity

Glacial loading and unloading is an important consideration in the assessment of seismic risk. Loading and unloading of the crust by continental ice sheets during glacial cycles alters the crustal stress regime, and creates compressive stresses, normal to the ice margin. A scientific review on issues related to glaciers, Ice Ages and the response of the earth to glacial cycles was carried out to summarize current knowledge and understanding of the influence of glacial cycles on the evolution of fault reactivation.

In the review by Wu (2009), the spatio-temporal variation of stress and fault stability induced by the stresses from glacial loading, bending of the lithosphere and relaxation of the mantle was investigated. The effect of stress changes associated with sedimentation and erosion processes and shear induced by glacier flow were also considered and found to be relatively unimportant. Various rock failure criteria were reviewed and the assumption of virtual faults and optimal orientation were discussed. Laurentide, Fennoscandia, and the British Isles ice sheets were used to demonstrate the spatio-temporal variation of the fault stability margin during glacial cycles. For loads with large horizontal extents (e.g. the Laurentide ice sheet), fault instability was suppressed by the weight of the load. However, this was not the case for small isolated ice caps where the effect of stress amplification becomes important.

The effects of tectonic stress and overburden, material properties, compressibility, mantle rheology and lithospheric ductile zones were also studied. It was found that a thrust background stress regime is able to explain the majority of observed data in Laurentia and Fennoscandia. The size of the ice sheet and its deglaciation history were found to have a large effect on the onset timing of earthquakes inside and outside the ice margin. Mantle rheology has a large effect on the onset time of earthquakes and the amplitude of the fault stability margin outside the ice margin, but has little effect on the onset timing and mode of failure within the ice margin. Mantle viscosity has a large effect on the rate of change in the stability margin within the ice margin for the next few thousand years after glaciation.

4.3.5 Greenland Analogue Project

NWMO continued its involvement in the Greenland Analogue Project (GAP) in collaboration with SKB and POSIVA. The objective of this four year project (2009-2012) is to advance the understanding of processes associated with glaciation and their impact on the long-term performance of a DGR. There are currently some uncertainties in the understanding of hydrological, hydrogeological and geochemical processes during glacial conditions - in particular regarding the hydraulic conditions at the base of an ice sheet and the potential penetration of glacial meltwater to repository depth. Current hydrological models used to simulate glacial conditions deal with these uncertainties by applying conservative assumptions. The GAP study aims to reduce current uncertainties about the hydrological, hydrogeological and geochemical processes during glacial conditions, and results from the study will lead to the improvement of glacial hydrological models and safety assessments.

Following on permafrost studies in the Canadian Arctic (Stotler et al., 2009a,b; Holden et al., 2009) and an introductory field campaign in 2008 near Kangerlussuaq, Greenland, the GAP field program began in 2009 and included the successful initiation of ice sheet and geosphere/geochemistry studies. Through an extensive field and modeling program, GAP will evaluate glacial hydrology, groundwater flow and groundwater composition (particularly redox conditions) at the base of a continental-scale ice sheet. In 2009, research conducted on the surface of the ice sheet included the installation of GPS stations, ground-based radar work, remote sensing of the study area and tracer tests conducted near the ice margin to look at water flow from the surface to the base of the ice sheet. Three boreholes were drilled in front of the ice sheet to investigate the depth of the permafrost in the area and to confirm the presence of a talik beneath a water body (Figure 4.15). Geochemical sampling of surface water bodies was also conducted. Preparations were made for drilling in 2010 through the ice sheet to the base in order to investigate temperature and pressure conditions.

In 2009, NWMO and NSERC jointly awarded Industrial Postgraduate Scholarships to University of Waterloo Ph.D. candidates Emily Henkemans and Mike Makahnouk. Both graduate students are conducting research as part of the GAP project and are participating in field, laboratory and modeling studies.

Figure 4.15: Drilling of an inclined borehole near a talik lake west of the ice margin as part of the Greenland Analogue Project 2009 field campaign.

4.3.6 Evolution of Deep Groundwater Flow Systems

In order to investigate the evolution of groundwater flow systems and their impact on the long-term performance of a DGR, the NWMO is actively collaborating with researchers at the University of Waterloo. The primary focus of the research activities is to refine numerical geoscience tools and methods to characterize groundwater flow systems. Numerical methods will be used to test descriptive conceptual geosphere models and to develop innovative modelling approaches to assess the influence of site characterization uncertainties on groundwater flow and transport predictions.

Sub-regional shield groundwater flow studies, previously carried out in collaboration with the University of Waterloo, have provided insight into the influence of a number of geosphere properties on deep groundwater flow dynamics and evolution (Sykes et al., 2003, 2004; Normani et al. 2007). Geosphere parameters and properties such as variable salinities, statistically varying fracture networks, and variable fracture zone permeability, width and porosity were investigated. These studies also provided a better understanding of the impact of glaciation on deep groundwater flow systems in Canadian Shield settings and demonstrated the use of a Mean Life Expectancy calculation as a performance measure for evaluating geosphere responses to modelling and parameter uncertainty. Given the high degree of spatial, geometrical and physical complexity involved with modelling the evolution of groundwater flow systems at depth in shield environments, numerical approaches to increase computation tractability were investigated. The outcome of the studies are presented in a Ph.D. thesis by Normani (2009). Drawing on previous studies (Sykes et al., 2003, 2004; Normani et al. 2007), numerical tools and methods to characterize groundwater flow system evolution are currently being developed to evaluate the following phenomena:

- Variable density simulations;
- Hydromechanical coupling;
- Comparison of MLE, particle tracks and transport travel times;
- Boundary condition case studies;
- Sub-gridding and sub-timing; and
- Temperature and change of state.

4.4 NUMERICAL TOOLS AND METHODS

4.4.1 Hydromechanical Enhancements to FRAC3DVS-OPG

A host rock for a potential deep geologic 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 a glacial load will be transmitted to the geosphere and may impact groundwater flow patterns at depth.

Increased stresses due to a glacier are not limited to the volume of rock directly beneath the ice. Increased stresses can also develop beyond the glacial front, caused by Poisson effects. In the numerical code currently used by NWMO (FRAC3DVS-OPG version 1.1.0), the implementation of hydromechanical coupling is limited to the case of purely vertical strain with lateral constraints (Guvanasen, 2007). Due to this limitation, a new, fully coupled module will be implemented in FRAC3DVS-OPG to improve the representation of hydromechanical and thermohydromechanical effects. The new module is being developed based on the thermohydromechanical formulation of Guvanasen and Chan (2000), and the equivalent poroelastic medium formulation of Guvanasen and Chan (2003).

4.4.2 FRAC3DVS-OPG Quality Assurance

Numerical groundwater modelling is becoming an increasingly valuable tool for characterizing the evolution of a flow system at a potential repository horizon. In order to increase confidence in model results, codes used by the NWMO are 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 (Therrien et al., 2004) meets the quality assurance requirements detailed in NWMO’s technical computing software procedure.

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. To increase numerical tractability and efficiency, researchers at the University of Waterloo are undertaking modifications of FRAC3DVS-OPG which will be released in version 1.2.0. The FRAC3DVS-OPG Version 1.1.0 was released in May 2008.

4.4.3 Application of COMSOL Multiphysics Code for Coupled THM Modelling

The work program with McGill University investigated the computational capabilities and accuracy of the COMSOL Multi-Physics code and its applicability for modeling thermo-hydro-mechanical processes in fluid-saturated porous media. During the work, the accuracy of the COMSOL code was established through comparisons with known, exact analytical solutions available in the literature for porous media. The accuracy of the computational routines for multi-dimensional thermo-hydro-mechanical problems obtained via COMSOL Multi-Physics were also verified through comparisons with results for the analogous problems obtained from a general purpose finite element code ABAQUS. The work concluded that COMSOL was a viable alternative to other finite element programs when solving thermo-hydro-mechanical problems for linear poroelastic materials saturated with fluid. It was noted that COMSOL is a flexible code that allows the user to modify and specify partial differential equations that need to be solved, for example in coupled problems where differential equations of poroelasticity are coupled with the heat conduction equation.

The study also examined the applicability of the COMSOL code to simulate a simple fractured rock mass using a single fracture zone. The study considered two approaches for simulating a fractured rock mass subjected to fluid pressure at the surface of a vertical fracture zone. One of the approaches is shown in Figure 4.16. The two approaches produced qualitatively similar results.

On the basis of this research, future work to evaluate the capability of COMSOL to include multiple fracture zones and their intersections, and the effect of ice sheet stresses on the fractures was recommended. The recommendations were taken into account in the development of a new work program with McGill University which commenced in January 2010.

(a)

(b)

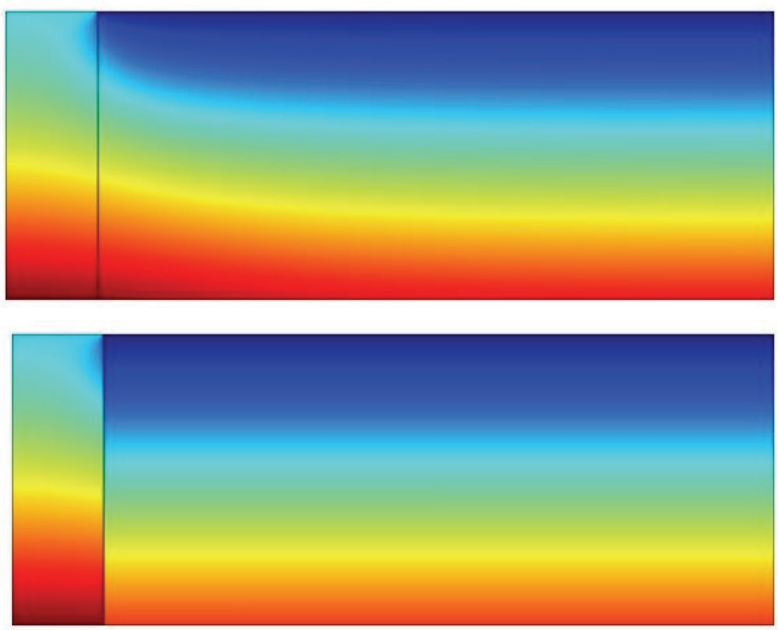

Figure 4.16: Geometry of the rock mass having a vertical fracture zone. The fluid pressure distribution inside the rock mass is shown for the (a) intact rock mass and for the (b) fractured rock mass. In this approach the fracture zone is represented by a thin layer in which transverse permeability is very small.

4.4.4 Äspö Modelling Taskforce

A modelling team from the Université Laval is participating in Äspö Task 7, which involves the numerical modelling of hydraulic responses in the fractured crystalline rock environment located on Olkiluoto Island in Finland. Investigations of POSIVA's Onkalo underground rock characterisation facility have generated a large data set which is being used in the modelling study.

Work conducted in 2009 focused on fluid flow modelling within Task 7B, which focuses on an area approximately 400 m by 400 m surrounding boreholes KR14 to KR18. The main goals of Task 7B were to quantify the reduction of uncertainty in the properties of the fracture network and to further assess the contribution of POSIVA Flow Log (PFL) data for rock mass characterization. The specific goals were to develop a conceptual model for the fractured rock and to perform forward and inverse modelling to reproduce the natural groundwater flow field and the hydraulic responses observed during pumping tests conducted in boreholes KR14 and KR18.

In 2009, the Laval modelling team participated in one Task Force meeting (TF#25 hosted by JAEA in Mizunami, Japan) and one modellers meeting (held in Lund, Sweden). The 2009 modelling activities for Task 7B included the implementation of a geostatistical approach (T-PROGS) characterized by a transitional probability model of categorical facies based on Markov chains to represent the fractured rock mass between the major fracture zones. Transmissive fractures identified with the PFL tool were used to define the fractured rock facies (Figure 4.17). The hydraulic response to pumping in the presence of open and sealed-off observation boreholes was simulated (Figure 4.17) and automatic model calibration was performed, using HydroGeoSphere and PEST, respectively. The conceptual model was adjusted to improve the match between observed and simulated hydraulic heads by testing different boundary conditions and by adding discrete fractures (Figure 4.17).

The main outcome of this work is the demonstration that PFL measurements are suitable for defining rock facies using the geostatistical approach adopted here, and that they are also extremely useful to improve model calibration. In particular, if PFL values are integrated as targets for model calibration together with head values, the uncertainty of model estimated parameters, which is evaluated from 95% linear confidence intervals, is reduced and the interpretation of inverse modelling results is more reliable.

Since the overall strategy of Task 7 is to progress from the Olkiluoto site-scale to a much smaller scale, upcoming Task 7C will consider small sub-volumes surrounding three ventilation shafts of Onkalo. The main goal is to use PFL data to characterize low transmissivity fractures. NWMO activities at the Äspö Hard Rock Laboratory are further described in the SKB Annual Report (SKB, 2009).

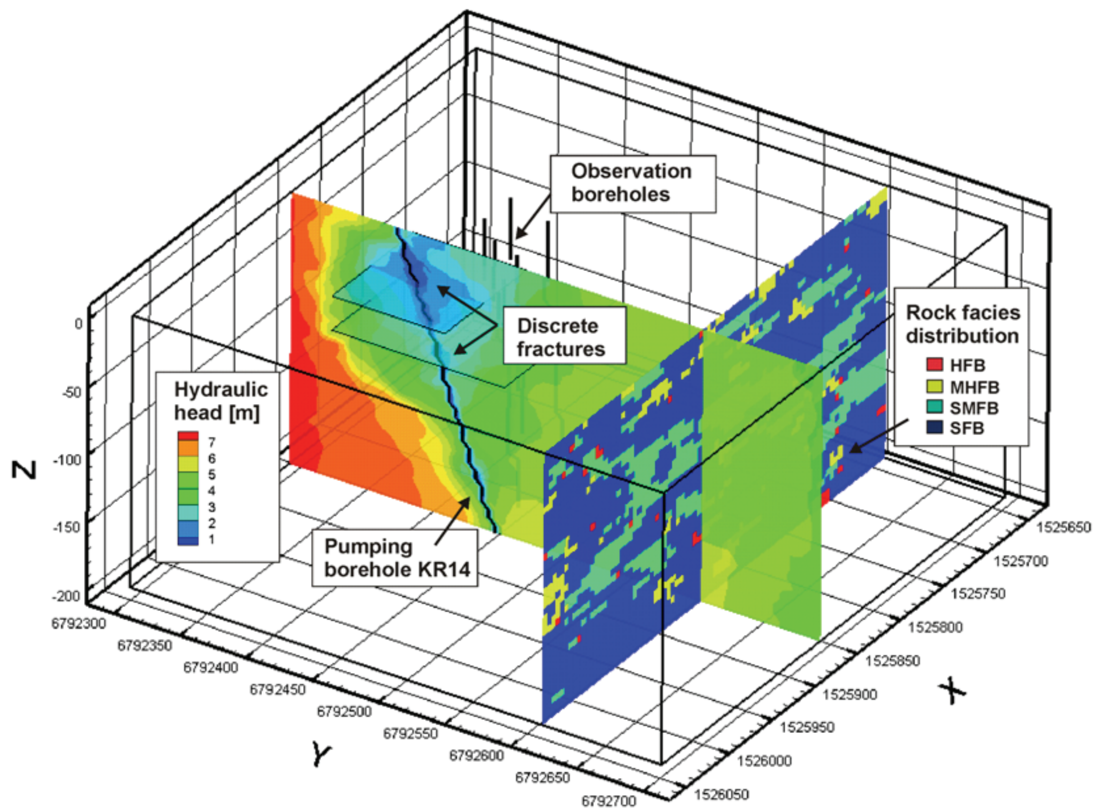

Figure 4.17: Two orthogonal slices within the 3D model show the fractured rock facies and the hydraulic head contours during pumping in borehole KR14. Two horizontal discrete fractures and location of observation boreholes are also shown.

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 (DGR) 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.

Garisto et al. (2009a) provides a technical summary of information on the safety of a DGR for used fuel. The report summarizes the key aspects of the geological repository concept and explains why the repository concept is expected to be safe (see, for example, Table 5.1). The report is non-site specific; it considers alternative geologic settings, specifically both the Canadian Shield and sedimentary rock formations; and encompasses several design concepts.

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

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. 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 DGR. 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 the corrosion process (Kremer et al., 2009). 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.

The 2009 experimental program on UO_2 dissolution, which was carried out at the University of Western Ontario, investigated the influence of: (1) H_2 inhibition of UO_2 corrosion in the presence of H_2O_2; (2) Fuel composition on the reactivity of UO_2: and (3) Corrosion product deposits on UO_2 dissolution. A combination of electrochemical and open circuit corrosion (E_{corr}) measurements on UO_2 electrodes and surface analytical techniques were used in the investigations (He et al. 2009a,b; Ofori et al. 2009). 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 (simulated high-burnup UO_2-based fuel) 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. The results of this University of Western research are summarized in sections 5.2.1.1 to 5.2.1.3.

5.2.1.1 Hydrogen Inhibition

In previous years, 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 (Kremer et al., 2009). In 2009, additional experiments were carried out to more fully understand this mechanism. In these experiments, corrosion potential measurements were performed on SIMFUEL electrodes in solutions purged with either Ar or 5% H_2/95% Ar to which H_2O_2 was added partway through the experiment.

In H_2O_2-containing solutions, UO_2 is oxidized by the reaction of H_2O_2 on both the UO_2 surface and the noble metal particles. These reactions proceed via the formation of OH• surface radicals. The OH• radicals formed on the noble metal particles can be scavenged by reaction with dissolved H_2 leading to a suppression of UO_2 oxidation. Since H_2 concentrations are many orders of magnitude greater than H_2O_2 concentrations, the rate of production of surface H• radicals on the noble metal particles is considerably larger than the rate for OH• formation. This leads to an eventual overwhelming of the UO_2 oxidation process. A $[H_2]/[H_2O_2]$ ratio of $\geq 10^6$ is sufficient to completely protect the UO_2 surface from oxidation.

Figure 5.1 and 5.2 illustrate the difference in the reactivity of H_2O_2 with UO_2 in the presence and absence of H_2. Figure 5.1a and Figure 5.1b show the final E_{corr} values achieved prior to (closed symbols), and after (open symbols), H_2O_2 addition in Ar and H_2/Ar purged solutions, respectively. In H_2/Ar, but not Ar-purged solutions, E_{corr} first rises to a maximum value before decreasing again. For the lower $[H_2O_2]$, E_{corr} decreases to the value established prior to H_2O_2 addition and, in a number of cases, drops to a value that is actually lower than the pre-addition value. For higher $[H_2O_2]$ (i.e. $[H_2O_2] > 10^{-10}$ mol/L), E_{corr} does not return to the pre-addition value but stabilizes at a more positive value, even for H_2/Ar-purged solutions. For the highest $[H_2O_2]$ employed (~10^{-9} mol/L), the final value in the H_2/Ar-purged solution is still ~180 mV less positive than the value recorded in Ar purged solution for this concentration.

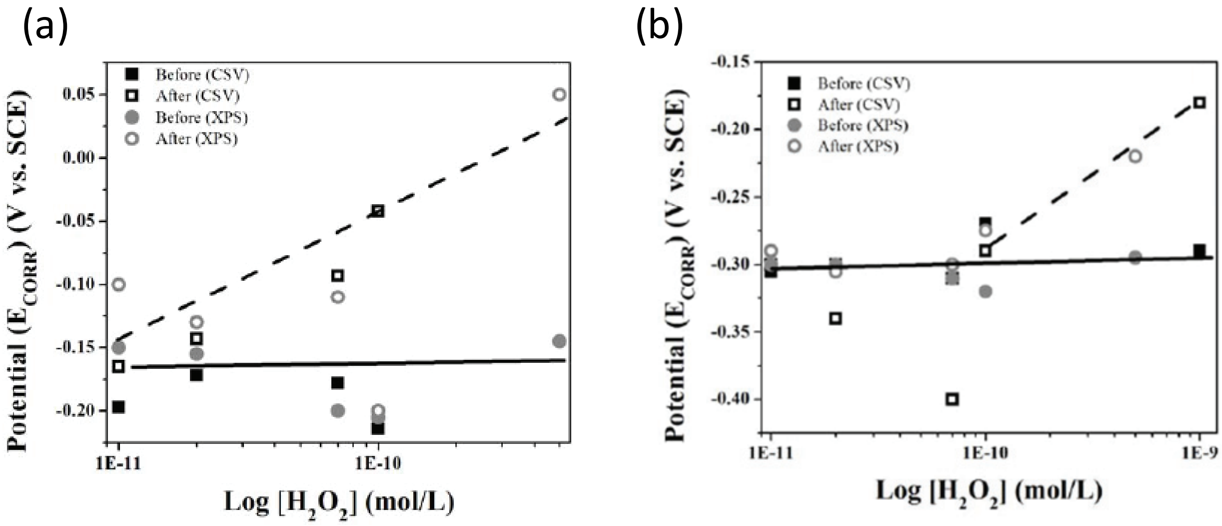

Figure 5.1: Final E_{corr} values recorded before (closed symbols) and after (open symbols) H_2O_2 addition. The purge gas was: (a) Ar; or (b) 5% H_2/95% Ar.

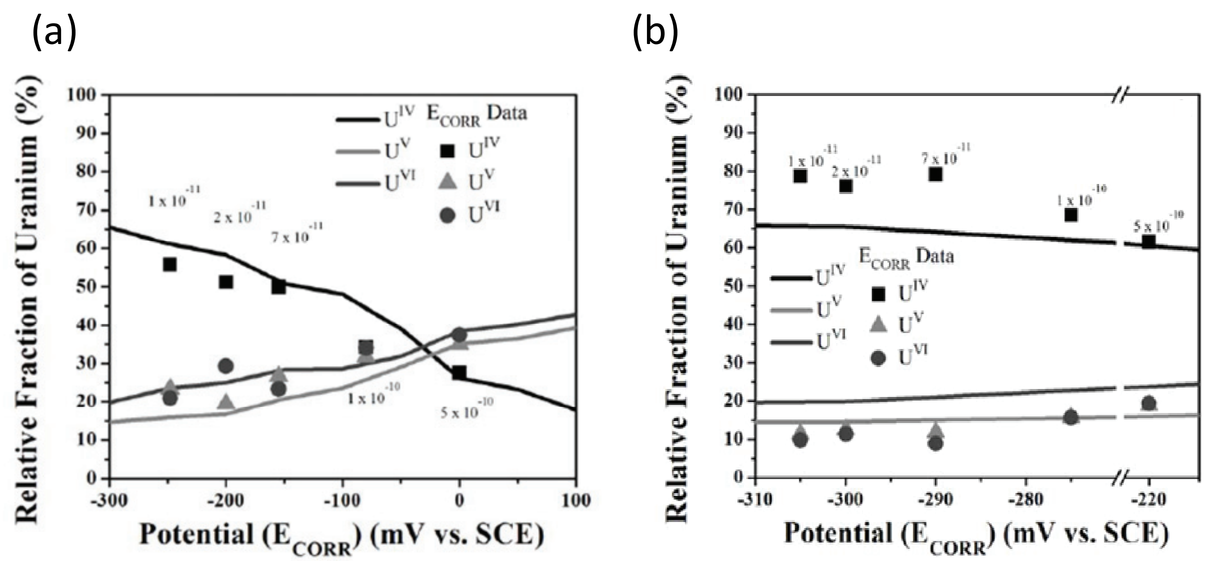

Figure 5.2: Surface UO_2 composition (as determined by XPS) of a 1.5 at. % SIMFUEL electrode containing ε-particles after E_{corr} measurements in (a) Ar or (b) 5% H_2/95% Ar purged solutions as a function of E_{corr} compared to calibration plots determined after electrochemical oxidation of the electrode at various individual potentials.

Figure 5.2 summarizes the XPS data as a function of the final steady-state E_{corr} value and compares it to the surface composition expected based on electrochemical oxidation of the surface (Broczkowski et al. 2007a). It was previously demonstrated that the surface U compositions obtained under corrosion conditions (i.e. at E_{corr}) in the presence of various (H_2/Ar, Ar, or O_2) purge gases followed these electrochemical calibration curves closely (Broczkowski et al. 2007a,b). In Ar-purged solutions this is also the case after corrosion in H_2O_2-containing solutions (Figure 5.2a). However, this is not the case when an H_2/Ar purge is used (Figure 5.2b).

The extent of oxidation is markedly lower than expected indicating that the combination of dissolved H_2 and low $[H_2O_2]$ can reduce the matrix U^V content of the electrode surface.

5.2.1.2 Influence of Degree of Fuel Non-Stoichiometry on Fuel Reactivity

Non-stoichiometry (x in UO_{2+x}) could exist at grain boundaries in the fuel, where lattice defects concentrate. Older fuels may have a higher degree of non-stoichiometry than currently manufactured fuels because fuel sintering was not as effective as it is today. Also, non-stoichiometry could be produced by vapour phase corrosion in a failed container prior to aqueous immersion. Since non-stoichiometry affects both the cathodic (H_2O_2 reduction) and anodic (UO_2 oxidation and dissolution) reactions, it is important to understand the effects of non-stoichiometry on fuel kinetics.

In 2009, the examination of a series of well characterized non-stoichiometric UO_{2+x} samples continued. A new method was developed to determine the distribution of corrosion rates at individual locations on a micrometer scale. The method is based on the use of scanning electrochemical microscopy (SECM) to measure probe approach curves and their correction for diffusion of the oxidant from the bulk solution using a finite element model. The technique was used to measure local corrosion rates on a UO_2 electrode with a nominal stoichiometry of 2.1 ($UO_{2.1}$). The rates were found to vary widely, due to the local variations in the degree of non-stoichiometry. Furthermore, the variations appeared to be between individual grains. Comparison to previous studies (He et al., 2009a) indicates the corrosion rate increases with the degree of local non-stochiometry.

5.2.1.3 Influence of Corrosion Product Deposits

In a geological repository, the redox conditions at the fuel surface will change with time as the strength of the alpha-radiation field decreases. Thus, oxidation of the fuel surface will likely change the composition of the fuel surface over the repository lifetime. This evolution is expected to cause accumulation of corrosion/dissolution product deposits on the surface of the fuel which could lead to the following effects: (1) They could block the fuel surface, which would reduce the exposed surface area and suppress the rate of fuel corrosion (Shoesmith, 2000); and (2) They could restrict the diffusive transport of species to (e.g. H_2 from steel corrosion) and from (e.g. radiolytically-produced H_2O_2) the reacting surface. This may lead to localized chemistries within the pores of the deposits on the fuel surface such as the development of localized acidity due to the hydrolysis of dissolved uranium (Shoesmith et al., 2003).

The physical and chemical properties of the deposits formed on the fuel surface will be determined primarily by the combination of redox conditions, temperature and groundwater composition (Shoesmith, 2000).

In 2009, electrochemical and surface analytical techniques were used to study the influence of silicate on the dissolution of SIMFUEL (Ofori et al., 2009). Although the concentration of silicon in Canadian Shield groundwaters is not large, its ability to form insoluble U^{VI} solids is well characterized. Surface analysis confirmed the formation of a uranyl silicate deposit on the SIMFUEL surface but the nature of the phase formed could not be confirmed.

In these experiments, the corrosion/dissolution of the SIMFUEL electrode was controlled galvanostatically. In the galvanostatic method, the electrode is subjected to a particular constant current density and the potential-time transient is measured. Since the reaction rate (i.e., the conversion of UO_2 to UO_2^{2+} in unit time) is proportional to the applied current, the overall reaction rate is fixed. In this manner, the influence of rate on the nature of corrosion product deposits, and the chemical conditions within them, can be studied.

At low current density ($I \leq 20$ nA/cm^2), oxidation and dissolution occur at a number of sites distributed across the electrode surface and the corrosion product deposit is thin and spreads laterally causing a shallow penetration depth profile. In contrast, at high current densities ($I \geq 100$ nA/cm^2), dissolution is restricted to a single site and the penetration depth at this site is deep and covered by a thick local deposit.

In the long-term experiments (200 to 500 hours), with current densities ≥ 20 nA/cm^2, a steady-state potential value of about 500 mV was achieved, indicative of local acidification. Scanning Electron Microscopy (SEM) micrographs indicate this acidification process occurred under deposits on the electrode surface and can lead to deep local dissolution sites. For a current density of 10 nA/cm^2, the potential only reached a value of about 250 mV, which may not be positive enough for acidification. As the current density was reduced further to 1 nA/cm^2, the potential appeared to stabilize around about 100mV, a value well below the ~250 mV threshold for the development of local acidity.

The Mixed-Potential Model (Shoesmith et al., 2003) predicts a maximum current density of about 1.5 nA/cm^2 for fuel corrosion over 10^6 years under expected Canadian repository conditions. This suggests that the development of acidification at occluded sites in the fuel surface is unlikely under the current waste disposal conditions. Hence, it is expected that used fuel dissolution rates would not be controlled by the localized chemistries within the pores of corrosion deposits but instead by uniform corrosion processes.

5.2.1.4 Alpha, Beta and Gamma Dose Rates

As noted above, the long-term release of radionuclides from used fuel is controlled by the dissolution rate of the fuel matrix. For the reducing conditions expected in a DGR, the rate of dissolution of the fuel in a failed container is expected to be controlled by the rate of generation of oxidants by radiolysis of groundwater, until the radiation fields have decayed to sufficiently low levels. Consequently, it is important to have good estimates of the alpha, beta and gamma dose rates near the fuel surface.

Garisto et al. (2009b) summarize the calculations used in previous studies assessing the alpha, beta and gamma dose rates near the surface of used fuel bundles in a used fuel container. These calculated dose rates will be used in future safety assessments, such as the upcoming Fourth Case Study (see Section 5.3.2).

5.2.2 Repository Modelling

The repository, also known as the "near-field" region, includes the waste, the container, the surrounding seals and 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. The research being conducted on container corrosion models is described in Section 3.2).

5.2.2.1 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 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 potentially released from the container.

In 2009, a project was initiated to quantify the effect corrosion products and varying defect size play on the release of radionuclides from both the container/buffer and buffer/host rock boundary. The role of corrosion products is complex. Corrosion products reduce void space in the container and provide additional sorption sites for radionuclides. On the other hand, corrosion products are also much less dense than the carbon steel and exert pressure on the copper container which could lead to expansion of the defect. However, the container copper shell and steel insert would still be present in some form and would still represent a physical constraint on both the rate of water access and the rate of radionuclide release.

In this project, several defect geometries were modelled to encompass a range of likely defect scenarios, both with and without the effect of corrosion products. Each failure scenario is treated as separate steady state model. The model geometries include: (1) Pinhole defect of 1 mm diameter (that enlarges subsequently by build-up of the corrosion products); (2) 10 mm hole; (3) 100 mm hole; (4) Cylindrical crack that runs around the diameter of the copper canister (10 mm wide); and (5) Complete failure of the canister (i.e. no copper remaining).

The results indicate that releases from the various failure scenarios agree with the expected trend in that the larger the defect, the larger the release from the container. In these models, the boundary conditions at the carbon steel insert controlled the release from the container at large copper defect sizes. Further modelling is planned.

5.2.2.2 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 the conditions expected around a deep repository and will therefore never mobilize in large amounts.

Solubilities are generally calculated using thermodynamic models which incorporate physical and chemical data for radionuclide elements and environmental conditions (water and mineral chemistry). There are a number of widely used thermodynamic datasets that support these models and there is on-going international work to improve the data.

NWMO continues to support the joint international Nuclear Energy Agency effort to develop chemical thermodynamic databases for elements of importance in the safety assessment of a geological repository for used fuel (Mompeán and Wanner, 2003). In late 2008, the thorium thermodynamic data report was published (Rand et al., 2008). In 2009, a draft report, for issue in 2010, describing the iron thermodynamic data was prepared and is currently undergoing peer review. Reviewers were also determined for the Mo thermodynamic data project, which will commence in 2010.

Throughout 2009, the solubilities of several key radionuclides used in safety assessment models were updated. Currently, there is not an unambiguous thermodynamic method to calculate solubilities under high salinity conditions so both Pitzer (Specific-ion Interaction) and SIT (Specific Ion Theory) approaches were used. Although both approaches used a PHREEQC format, the Pitzer and SIT approaches used the Yucca Mountain Project Dataset and ANDRA ThermoChimie v6 Dataset, as their thermodynamic databases, respectively.

The solubilities of Np, Pu, Se, U, and Zr were calculated in reference crystalline (CR-10) and sedimentary (SR-160) water compositions using both approaches. The Pitzer and SIT approaches produced very similar solubility results, as illustrated in Table 5.2 for the crystalline reference groundwater CR-10. The interaction of the buffer materials and the container on the groundwater chemistry was also included in the solubility calculations (Table 5.2).This project may be extended to compute the solubilities of a suite of other radionuclides, given the availability of thermodynamic data. The development and composition of the reference groundwaters are further discussed in Section 5.2.3 and Table 5.3.

Table 5.2: Comparison Between Solubility Calculations Performed Using Two Databases for radionuclides in CR-10 Crystalline Rock Groundwater

Element		Solid	ThermoChimie / SIT		Yucca Mountain Project / Pitzer	
			Concentration (m)	**Aqueous species**	**Concentration (m)**	**Aqueous species**
Se	A	$FeSe_2$	$1.1 \cdot 10^{-10}$	HSe^- (100%)	--	--
	B		$1.3 \cdot 10^{-8}$			
Pu	A	$PuPO_4$	$5.1 \cdot 10^{-12}$	Pu^{3+} (31%), $PuSO_4^+$ (31%), $PuCO_3^+$ (23%), $Pu(OH)^{2+}$ (9%)	$1.1 \cdot 10^{-12}$	Pu^{3+} (82%), $PuCO_3^+$ (12%)
	B		$8.9 \cdot 10^{-13}$	$Pu(OH)^{2+}$ (47%), $PuPO_4$ (12%), $PuSO_4^+$ (11%), $Pu(OH)_2^+$ (9%), $PuCO_3^+$ (7%)	$6.6 \cdot 10^{-12}$	Pu^{3+} (100%)*
Np	A	NpO_2(am)	$1.1 \cdot 10^{-9}$	$Np(OH)_4$ (93%)	$1.3 \cdot 10^{-9}$	$Np(OH)_4$ (95%)
	B		$1.0 \cdot 10^{-9}$	$Np(OH)_4$ (100%)	$1.2 \cdot 10^{-9}$	$Np(OH)_4$ (100%)
U	A	UO_2(am)	$3.5 \cdot 10^{-9}$	$U(OH)_4$ (91%)	$1.0 \cdot 10^{-8}$	$UO_2(CO_3)_3^{4-}$ (44%), $U(OH)_4$ (38%), $UO_2(CO_3)_2^{2-}$ (16%)
	B		$3.2 \cdot 10^{-9}$	$U(OH)_4$ (100%)	$3.8 \cdot 10^{-9}$	$U(OH)_4$ (100%)
Zr	A	$Zr(OH)_4$(am)	$1.8 \cdot 10^{-8}$	$Zr(OH)_4$ (100%)	--	--

A: Groundwater composition equilibrated with minerals
B: Groundwater composition reacted with carbon steel container and bentonite

5.2.2.3 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 to release them. 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. Gas transport modelling was 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 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 2009, Intera obtained a license for TOUGH2-MP, a parallel version of the TOUGH2 code. This code has been altered to include LASGIT specific functions and substantially improve the output algorithm for time dependent data from grid-blocks, connections, and source/sink nodes.

Results of the preliminary gas tests at LASGIT in 2008 are difficult to interpret, but do not seem to indicate that a gas breakthrough has occurred. It is hoped that the second round of gas injection tests in 2010 will provide stronger and less equivocal data for modelling. Permeability of the host rock may provide a very important parameter for interpretation of experimental results.

Despite the lack of gas migration data provided by the preliminary gas tests, modelling of the gas injection tests provided some insight into gas transport within the bentonite and highlighted required areas for model improvement.

5.2.3 Geosphere Modelling

The development of improved geosphere models is largely carried out under the Geoscience work program. Recent safety assessment case studies have used both detailed geosphere models and system-level safety assessment models. In particular, the Third Case Study and Third Case Study/Horizontal Borehole Concept studies (Gierszewski et al., 2004b, Garisto et al., 2005) have used a regional study model similar to that used in on-going Geoscience numerical studies, and the FRAC3DVS code (see Section 4.4.1) to provide detailed 3-D groundwater flow and transport analyses. This ensures that the same geosphere conceptual model is being used by both the geoscience and safety assessment groups. The Fourth Case Study, initiated in 2009 (see Section 5.3.2), considers crystalline rock and is an update of the Third Case Study.

Geochemical modelling, sorption experiments, solubility calculations, and safety assessment calculations require reference groundwaters to ensure consistency. For the hypothetical failure of a used fuel container, the solubility of radionuclides released from the container will depend on the chemistry of the groundwater. The sorption of radionuclides onto the engineered barrier materials and the host rock will also depend on the groundwater chemistry, as will potential geochemical reactions. Appropriate selection of reference groundwater compositions is, therefore, essential to obtain sound solubility values.

Reference waters are standardized compositions which are representative of a certain rock type or a certain set of near-field conditions. Since NWMO is currently considering both sedimentary and crystalline rocks as potential hosts for a DGR, representative groundwaters for both rock types were defined in 2009. The groundwater compositions are based on measurements over many observed groundwater samples, and do not represent a specific site.

This set of representative groundwaters (two of which are presented in Table 5.3 for information) are analogous to groundwaters that are likely to be found in potential geological used fuel repository sites within Canada. They cover a range of depths, rock types, and salinities and as such assist in current and future modelling activities.

Table 5.3: Illustrative Deep Groundwater Compositions

Groundwater Type	Crystalline Rock CR-10	Sedimentary Rock SR-160
Nominal pH	7	6.5
Environment Type	Reducing	Reducing
Nominal E_H (mV)	-200	-200
Solutes (mg/L)		
Na	1,900	37,000
K	15	1,780
Ca	2,130	14,700
Mg	60	3,900
HCO_3	70	50
SO_4	1,000	420
Cl	6,100	97,600
Br	-	570
Sr	25	510
Li	-	7
F	2	5
I	-	90
Si	5	10
Fe	1	30
NO_3	<1	<10
PO_4	0	-
Total dissolved salts (mg/L)	11,300	157,000

5.2.4 Biosphere Modelling

5.2.4.1 Iodine in the Biosphere

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).

In 2009, the three year study and sampling campaign was completed. Sampling focused on aquatic and terrestrial ecosystems as well as domestic farm environments. Key transfer factor data and other ancillary media parameters were measured for a number of biota of interest to safety assessment case studies (e.g. fish, cow, chicken, wild game, berries).

Over the three year study, 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. Results show good agreement between measured transfer factor results and plant/soil concentration ratios for iodine compared to those of Sheppard et al. (2002). In many cases, substantial improvements were made to the number of measurements and distribution of a particular transfer factor or concentration ratio when compared with the literature review (see Figure 5.3).

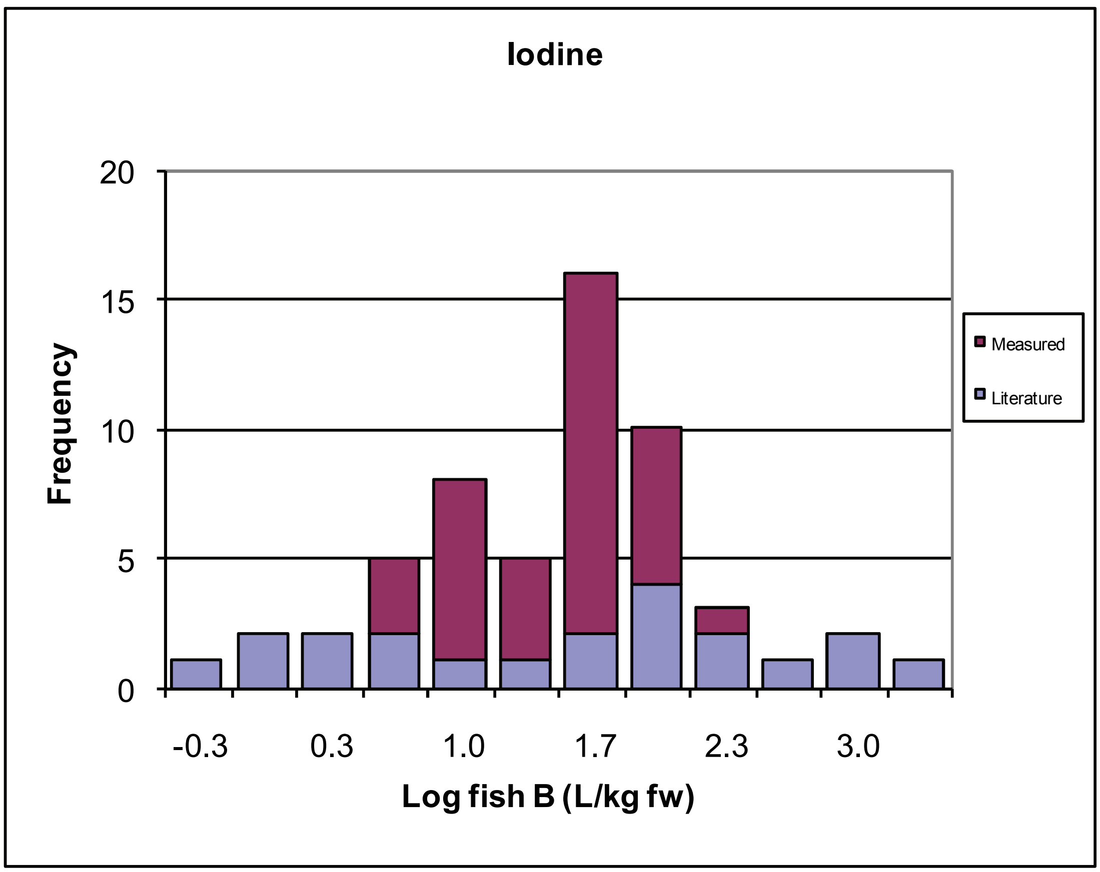

Figure 5.3: Iodine transfer factor data from the literature (blue) compared to additional transfer factors measured by Sheppard et al. (2009) from 2007-2009.

A cumulative report (Sheppard et al., 2009) presenting all the results of the three year study was published in 2009 and several scientific papers are expected to be published in 2010.

5.2.4.2 Environmental Radioactivity

Postclosure safety assessments use environmental concentrations and fluxes of radionuclides as long-term safety indicators. Knowledge of background radioactivity is useful as a criterion or reference point for these indicators, especially if the data are regionally appropriate. Work was completed in 2009 to review and summarize the background concentrations of radionuclides in surface water and soil across Canada.

Three types of radionuclides were considered. The first radionuclides were primordial, including parents and progeny of ^{235}U, ^{238}U and ^{232}Th, ^{40}K and ^{97}Rb. The second were rare but naturally occurring radionuclides of special interest, including ^{3}H, ^{14}C, ^{36}Cl and ^{129}I. The third were fallout radionuclides with emphasis on ^{3}H, ^{14}C, ^{137}Cs and ^{90}Sr. Data were obtained specifically for Canadian sites, however, data from international sources were also included as needed. Contaminated sites were avoided, but associated control-site data were evaluated.

The amount of data for concentrations in the environment is quite variable among radionuclides. There is more data for radionuclides that are easy to measure, and much fewer for the others. Some of the rarely measured, such as ^{14}C, ^{36}Cl and ^{129}I require expensive accelerator mass spectroscopy methods to detect environmental concentrations. For these radionuclides, ratios with their stable isotopes are especially useful when assessing background concentrations. Additional measurements will be performed in 2010 to supplement the review prior to its publication.

5.2.5 Integrated System Model

The postclosure safety assessment of a used fuel repository uses several complementary computer models, as shown in Table 5.4. These are either commercially maintained codes, or codes maintained by NWMO under a software quality assurance system.

Table 5.4: Main Safety Assessment Codes for Postclosure Analyses

Software	Description / Use
SYVAC3-CC4	NWMO reference integrated system model
FRAC3DVS	3D groundwater flow and transport model
TOUGH2	3D two-phase gas and water flow model
AMBER	Generic compartment model
COMSOL	3D multi-physics finite element model
MICROSHIELD	Radioactive shielding and dose model

In 2008, the SYVAC3-CC4 system model was modified by addition of climatic states. SYCAC3-CC4 can now be used to evaluate the effect of time changes in geosphere and biosphere conditions, such as would occur during a glacial cycle. In 2009, the new system model was tested, verified, and used in the safety assessment of a glaciation scenario (see Section 5.3.1).

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 NWMO's 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 DGR concept in the Canadian Shield. Each of the above studies considered a different combination of engineering design and site characteristics. The glaciation scenario and planned "Fourth Case Study" are outlined below.

5.3.1 Glaciation Scenario

The NWMO 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 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 previous Canadian case studies, the effects of glaciation have been considered in geoscience studies and in engineering the design of the repository. The potential impacts of glaciation on safety and performance have also been evaluated qualitatively but not quantitatively. Therefore, starting in 2007, the effects of an evolving climate with multiple glaciations have been quantitatively evaluated, from a safety assessment perspective, within the context of the hypothetical Third Case Study site on the Canadian Shield. The purpose of this "Glaciation Scenario" case study is to quantitatively assess the long-term dose implications of glacial cycles for a DGR, and to understand the key factors involved. The results of the glaciation study will be published in 2010.

The detailed three-dimensional modelling results confirmed the expected impact of glaciation on the velocity and direction of the groundwater flow system. The modelled effects were greatest near the surface but extended to the repository level (Figure 5.4). The open taliks during Permafrost States, in particular, are a dominant factor, focusing system impacts at a discrete location. (An open talik is a layer of year-round unfrozen ground that lies in permafrost, generally below a large lake). Furthermore, the transport calculations indicated that radionuclide mass flows to the surface biosphere are quite different in detail for the transient glaciation model compared to the equivalent constant climate case, but the overall trends are similar.

For the Glaciation Scenario, the safety assessment calculations indicated that the calculated dose rates are highest during the Temperate State (Figure 5.5). This occurs because the critical group during the Temperate State uses a well, rather than a lake, as its domestic water source and nuclide concentrations in well water are typically several orders of magnitude higher than in lake water. In the Glaciation Scenario Reference Case, the calculated peak total dose rate is about $3.7x10^{-7}$ Sv/a, with I-129 contributing the most to the total dose rate. This is similar to the peak dose rate of $1.3x10^{-7}$ Sv/a for the corresponding constant climate case and well below the dose rate constraint of $3x10^{-4}$ Sv/a recommended by International Commission on Radiological Protection (ICRP) for disposal of long-lived solid radioactive waste and the average Canadian natural background dose rate of 1.8 $x10^{-3}$ Sv/a (Figure 5.5).

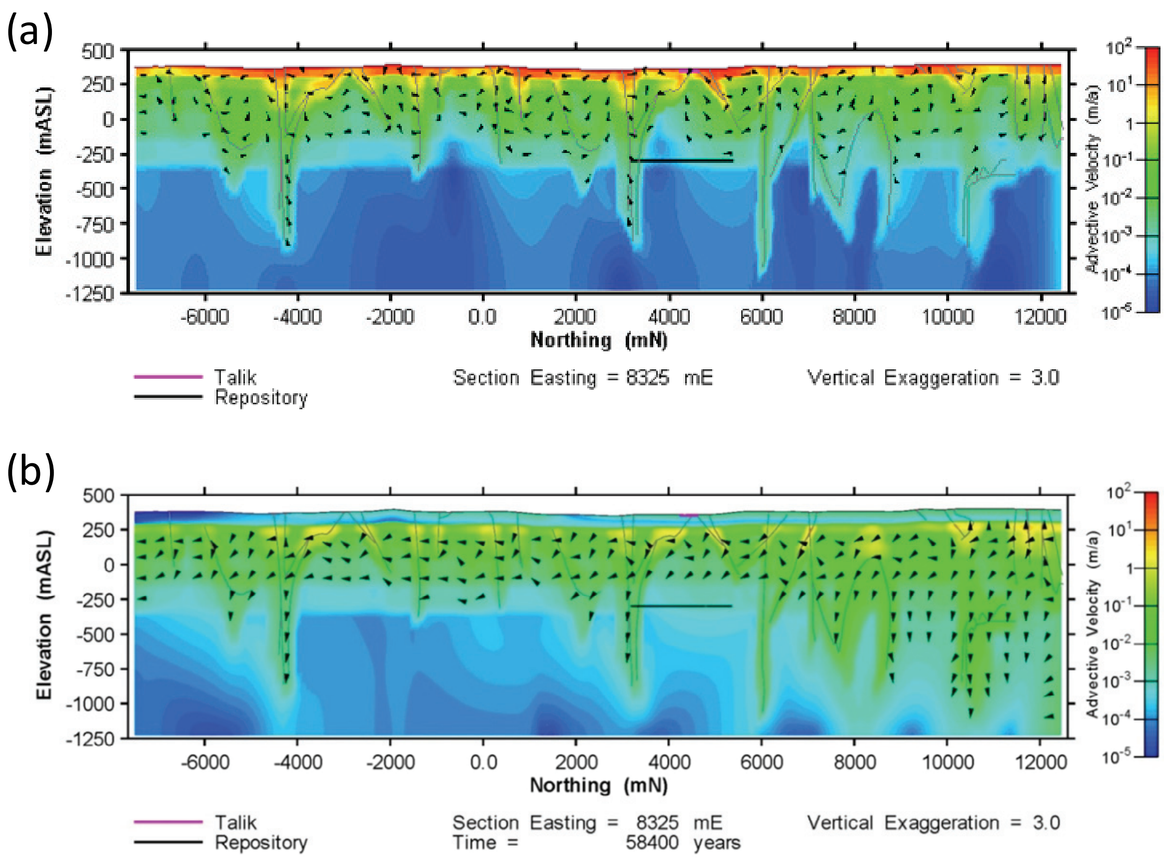

Figure 5.4: The Glaciation Scenario Reference Case flow model results during: (a) the initial temperate state; and (b) beginning of ice sheet state. The advective velocity distribution is shown by colour and velocity vectors are plotted where the velocity exceeds 1 mm/a.

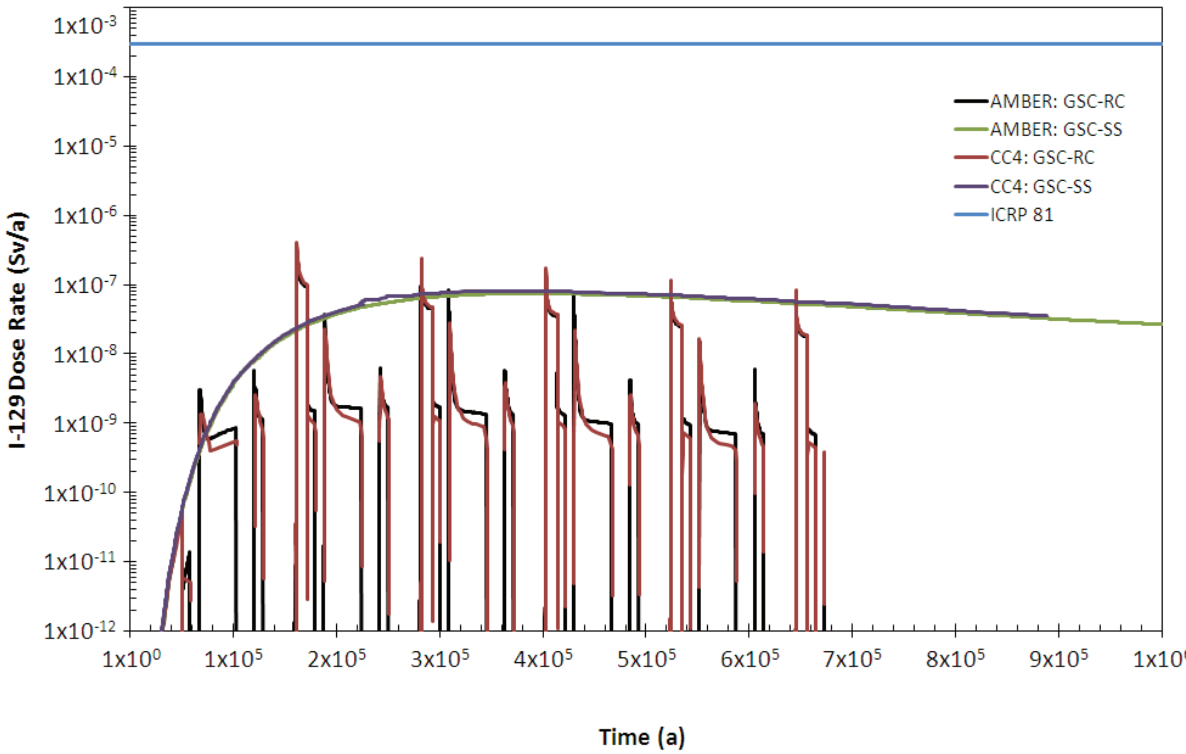

Figure 5.5: I-129 Dose rates calculated using the I-129 discharges into the biosphere from FRAC3DVS for the Glaciation Scenario Reference Case (GSC-RC) and the AMBER or CC4 Biosphere Models. The dose rates calculated using the I-129 geosphere discharges for the Constant (Temperate) Climate model (GSC-SS with a well) are shown for comparison.

A series of sensitivity cases and probabilistic cases were also investigated. Of particular interest is the Climate State Duration probabilistic case. In this probabilistic case, the duration of the various climate states (i.e. Temperate, Permafrost, Ice Sheet and Proglacial Lake) was varied randomly. Except for the duration, these states were assumed to have the same characteristics (i.e., geosphere and biosphere properties) as those in the Glaciation Scenario Reference Case. The results for this case suggested that varying the glacial cycle could lead to higher calculated dose rates compared to the Reference Case (see Figure 5.6). Although the 90th percentile calculated dose rate in this probabilistic simulation was 3-fold higher than in the Reference Case, it remained well below the dose rate constraint recommended by ICRP.

In summary, for the Third Case Study hypothetical site and repository, calculated peak dose rates for the Glaciation Scenario were approximately of the same order of magnitude as for the corresponding constant (temperate) climate scenario. The calculated peak dose rates for the Glaciation Scenario were well below the ICRP dose constraint and the average natural Canadian background dose rate. Thus, it can be concluded that for the hypothetical Third Case Study site and repository, the impacts of a DGR would be well below regulatory limits even when the effects of glaciation are considered (see Figure 5.5).

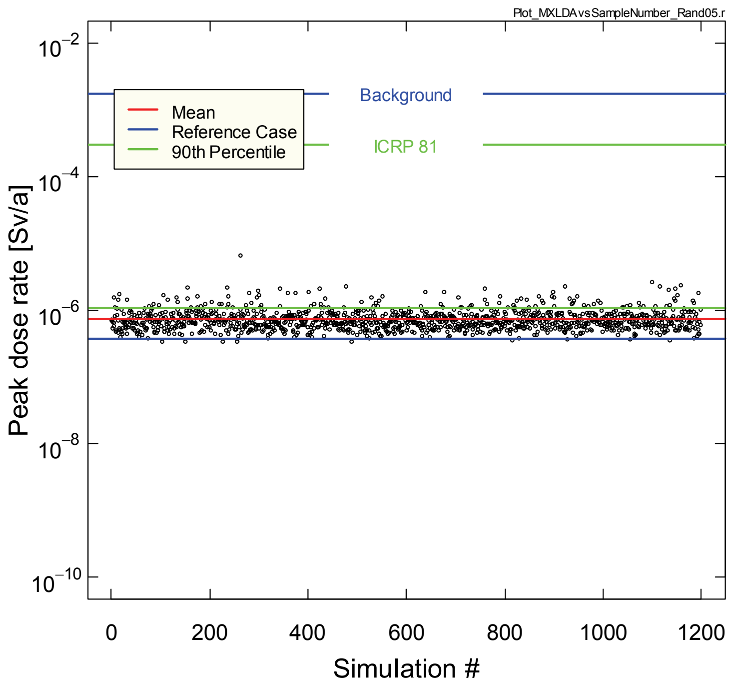

Figure 5.6: Calculated peak dose rates for the climate state duration probabilistic case.

5.3.2 Fourth Case Study

A new safety assessment for a DGR for used fuel in crystalline rock will be undertaken in 2010. This case study is nominally named the Fourth Case Study. The repository is assumed to be at a depth of 500 m and at a site broadly similar to the hypothetical Third Case Study site on the Canadian Shield (Gierszewski et al., 2004b). The safety assessment will examine a new repository design (with in-floor container emplacement) and the current reference (larger) container design. In 2009, preparatory work for the Fourth Case Study was initiated, in particular, data compilation and review.

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Vilks, P. 2009. Sorption in Highly Saline Solutions – State of the Science Review. Prepared by Atomic Energy of Canada Limited. Nuclear Waste Management Organization Report NWMO TR-2009-18. Toronto, Canada.

Vilks, P., N.H. Miller. 2009. Bentonite and Latex Colloid Migration Experiments in a Granite Fracture on a Metre Scale to Evaluate Effects of Particle Size and Flow Velocity. Nuclear Waste Management Organization Report NWMO TR-2009-26 Toronto, Canada.

Wu, P. 2009. State-of-the-Science Review of the Stress Field during a Glacial Cycle and Glacially Induced Faulting. Nuclear Waste Management Organization Report NWMO TR-2009-09. Toronto, Canada.

APPENDIX A: LIST OF TECHNICAL REPORTS, PAPERS AND CONTRACTORS

A.1 NWMO Technical Reports

Kremer, E., 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. 2009. Technical research and development program for long-term management of Canada's used nuclear fuel – Annual report 2008. Nuclear Waste Management Organization Report NWMO TR-2009-01. Toronto, Canada.

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Spiessl[1], S.M., K.U. Mayer[1] and K.T.B. MacQuarrie[2]. 2009. Reactive Transport Modelling in Fractured Rock – Redox Stability Study. Prepared by [1]Department of Earth and Ocean Sciences, University of British Columbia; [2]Department of Civil Engineering, University of New Brunswick. Nuclear Waste Management Organization Report NWMO TR-2009-04. Toronto, Canada.

Hayek, S., J.A. Drysdale, V. Peci, S. Halchuk, J. Adams and P. Street. 2009. Seismic activity in the Northern Ontario portion of the Canadian Shield – Annual progress report for the period January 01-December 31,2008. Prepared by the Canadian Hazards Information Service, Geological Survey of Canada. Nuclear Waste Management Organization Report NWMO TR-2009-05. Toronto, Canada.

King, F.[1] and M. Kolar[2]. 2009. Theory Manual for the Steel Corrosion Model Version 1.0. Prepared by [1]Integrity Corrosion Consulting Ltd.; [2]LS Computing Ltd. Nuclear Waste Management Organization Report NWMO TR-2009-07. Toronto, Canada.

Shek, G.K. and B.S. Wasiluk. 2009. Development of Delayed Hydride Cracking Test Apparatus and Commissioning Tests for CANDU Fuel Bundle Assembly Welds. Prepared by Kinectrics Inc.. Nuclear Waste Management Organization Report NWMO TR-2009-08. Toronto, Canada.

Wu, P. 2009. State-of-the-Science Review of the Stress Field during a Glacial Cycle and Glacially Induced Faulting. Prepared by University of Calgary. Nuclear Waste Management Organization Report NWMO TR-2009-09. Toronto, Canada.

Stotler[1], R.L., S.K. Frape[1], T. Ruskeeniemi[2], L. Ahonen[2], M. Paananen[2] M.Y.Hobbs[3], K. Lambie[1], and M. Zhang[1]. 2009. Hydrogeochemistry of groundwaters at and below the base of the permafrost at Lupin: Report of Phase III. Prepared by [1]University of Waterloo, [2]Geological Survey of Finland, [3]Nuclear Waste Management Organization. Nuclear Waste Management Organization Report NWMO TR-2009-10. Toronto, Canada.

Holden, B.[1], R.L. Stotler[1], S.K. Frape[1], T. Ruskeeniemi[2], M. Talikka[2], B.M. Freifeld[3]. 2009. High Lake Permafrost Comparison Site: Permafrost Phase IV. Prepared by [1]University of

Waterloo; [2]Geological Survey of Finland; [3]Lawrence Berkeley National Laboratory. Nuclear Waste Management Organization Report NWMO TR-2009-11. Toronto, Canada.

Garisto, F., T. Kempe and P. Gierszewski. 2009. Technical Summary of the Safety Aspects of the Deep Geological Repository Concept for Used Nuclear Fuel. Nuclear Waste Management Organization Report NWMO TR-2009-12. Toronto, Canada.

Leech, R.E.J., T.L. Wlodarczyk, S. Davies, M. Lee. 2009. Feasibility of Using Geoscientific Criteria for Early Screening of Large Geographic Areas that would be Unsuitable for Safely Hosting a Deep Geological Repository. Prepared by AECOM Canada Ltd. Nuclear Waste Management Organization Report NWMO TR-2009-13. Toronto, Canada.

Stahmer, U. 2009. Transport of Used Nuclear Fuel – A Summary of Canadian and International Experience. Nuclear Waste Management Organization Report NWMO TR-2009-14. Toronto, Canada.

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Seager, M. and Inglot, A. 2009. ORIGEN-S Decay Heat Calculations from NuFLASH and SORO Detailed Bundle Data. Prepared by AMEC-NSS. Nuclear Waste Management Organization Report NWMO TR-2009-33. Toronto, Canada.

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A.2 Publications and Presentations

Refereed Journals

Atkinson, G.M., N. Kraeva. 2010. Ground Motions Underground Compared to Those on Surface: A Case Study from Sudbury, Ontario, Bulletin of the Seismological Society of America. In press.

Cavé, L. T. Al, Y. Xiang and P. Vilks. 2009. A technique for estimating one-dimensional diffusion coefficients in low-permeability sedimentary rock using X-ray radiography: Comparison with through-diffusion measurements. Journal of Contaminant Hydrology. 103. 1-12.

He, H. Ding, Z., Shoesmith, D.W. 2009. The determination of electrochemical activity and sustainability on individual hyper-stoichiometric UO_{2+x} grains by Raman microspectroscopy and scanning electrochemical microscopy. Electrochemistry Communications, 11(8): 1724-1727.

He, H., R. Zhu, Z. Qin, P. Keech, Z.F. Ding and D.W. Shoesmith. 2009. Determination of local corrosion kinetics on hyper-stoichiometric U O2+x by scanning electrochemical microscopy. Journal of the Electrochemical Society, 156, C87.

Lampman, T.A., Popescu, and J. Freire-Canosa. 2009. Comparison of CANDU Fuel Bundle Finite Element Model with Unirradiated Mechanical Load Experiments. Journal of ASTM International, Vol.6(3).

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Stroes-Gascoyne, S., C.J. Hamon, P. Maak and S. Russell. 2010. The effects of the physical properties of highly compacted smectitic clay (bentonite) on the culturability of indigenous microorganisms. Applied Clay Science, 47, 155-162.

Reports

Snell, J. 2009. Mechanical Deformation Tests on 37 and 28 Element Fuel Elements. Stern Laboratories Report SL-205. Hamilton, Canada.

Conferences and Sessions Chaired

American Geophysical Union 2009 Joint Assembly, The Meeting of the Americas (Toronto, 24–27 May, 2009), Session “Hydrogeology of Subsurface Radioactive Waste Disposal” chaired by M. Jensen (NWMO) and R. L. Beauheim, Sandia National Laboratories Repository Performance Department.

Spent Fuel Workshop (Toronto, May 7-8, 2009). Organized by F. Garisto (NWMO) and D. Shoesmith (University of Western Ontario).

Conference Presentations

Al, T.A., Y Xiang, L Cavé, D Loomer, P Vilks, L Van Loon. 2009. Diffusion Measurements in Low-Permeability Ordovician Sedimentary Rocks From Southern Ontario. Presented at the American Geophysical Union Joint Assembly, The Meeting of the Americas, May, 24–27. 2009, Toronto, Canada.

Ben Belfadhel, M. 2009. The Long-term Management of Used Nuclear Fuel in Canada A Geoscientific Prespective. Presented at the American Geophysical Union Joint Assembly, The Meeting of the Americas, May, 24–27. 2009, Toronto, Canada.

Freire-Canosa, J. The Used Fuel Integrity Program at the NWMO. Presented at the Spent Fuel Workshop, May 7-8, 2009. Toronto. Canada.

Garisto, F. Alpha, Beta, Gamma Dose Rates in Water in Contact with Used CANDU fuel. Presented at the Spent Fuel Workshop, May 7-8, 2009. Toronto. Canada.

He, H. Determination of Local Corrosion Kinetics on Hyperstoichiometric UO_2 using Scanning Electrochemical Spectroscopy. Presented at the Spent Fuel Workshop, May 7-8, 2009. Toronto. Canada.

Kwong, G. Anaerobic Corrosion of Carbon Steel under Unsaturated Conditions in a Nuclear Waste Deep Geological Repository. Presented at EUROCORR 2009, Nice, France. September 10, 2009.

Kwong, G. Understanding of the Corrosion Processes of a Copper Used Fuel Container. Presented at EUROCORR 2009, Nice, France. September 10, 2009.

Marklund, L., S Xu and A Worman. 2009. Characterization of Discharge Areas of Radionuclides Originating From Nuclear Waste Repositories. Presented at the American Geophysical Union Joint Assembly, The Meeting of the Americas, May, 24–27. 2009, Toronto, Canada.

Normani, S.D., Sykes, J.F., Yin, Y. 2009. Paleoclimate Impact on a Proposed Canadian Deep Geologic Repository for Low and Intermediate Level Radioactive Waste. Presented at the American Geophysical Union Joint Assembly, The Meeting of the Americas, May, 24–27. 2009, Toronto, Canada.

Read, R.S. and K. Birch. 2009. Reasoned Argument Why Large-Scale Fracturing will not be Induced by a Deep Geological Repository. Presented at the Rock Eng09, the 3rd Canada-US Rock Mechanics Symposium. May 2009. Toronto. Canada.

Read, R.S. and K. Birch. 2009. The Role of Rock Engineering in Developing a Deep Geological Repository in Sedimentary Rocks. Presented at the Rock Eng09, the 3rd Canada-US Rock Mechanics Symposium. May 2009. Toronto. Canada.

Sergio, A. B., K. U. Mayer and K.T.B. MacQuarrie. 2009. Regional groundwater flow and geochemical processes within an intercratonic sedimentary basin affected by long-term episodes of freshwater recharge. Presented at the American Geophysical Union, AGU Fall Meeting, December 14-18, 2009, San Francisco, California, USA.

Sykes, J.F., S D Normani, Y Yin, E A Sykes. 2009. Regional and Site-Scale Hydrogeologic Analyses of a Proposed Canadian Deep Geologic Repository for Low and Intermediate Level Radioactive Waste. Presented at the American Geophysical Union Joint Assembly, The Meeting of the Americas, May, 24–27. 2009, Toronto, Canada.

Vorauer, A., Ben Belfadhel, M., Hischorn, S., and Garisto, F. 2009. Understanding the Impact of Future Glaciation on the Performance of a Canadian Deep Geologic Repository for Used Nuclear Fuel. Presented at the Geological Society of America Annual Meeting, October 18-21, 2009, Portland, Oregon, USA.

Wanne, T.S. 2009. Bonded-particle simulation of Tunnel Sealing Experiment. Presented at the RockEng09, the 3rd Canada-US Rock mechanics symposium. May 2009. Toronto. Canada.

Wanne, T.S. 2009. Seismic Response of Heated Westerly Granite – Numerical Simulation. Presented at the Timodaz conference and workshop: Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories. 29th September - 1st October 2009. Luxembourg.

West, J.M., I.G. McKinley, S. Stroes-Gascoyne. 2009. Implications of microbial redox catalysis in analogue systems for repository safety cases. Paper ICEM2009-16336, presented at ICEM 2009, October 11-15, 2009, Liverpool, UK .

Invited Presentations

Ben Belfadhel, M., R. Frizzell. 2009. The Long-term Management of Canada's Used Nuclear Fuel. Saskatchewan Research Council, Jun. 22.

Ben Belfadhel, M., S. Hirschorn, R. Frizzell. 2009. The Long-term Management of Canada's Used Nuclear Fuel. Alberta Research Council. Feb. 4

Ben Belfadhel, M. 2009. The long-term management of used nuclear fuel in Canada. Hydro-Quebec, Montreal, Dec. 15.

Ben Belfadhel, M. 2009. The long-term management of used nuclear fuel in Canada, Gentilly Nuclear Station, Trois Rivieres, Dec. 15.

Birch, K. 2009. Long Term Management of Canada's Used Nuclear Fuel. Faculty of Nuclear Energy Systems and Nuclear Engineering University of Ontario Institute of Technology, Oct. 19.

Gierszewski, P. 2009. Radioactive Waste Management in Canada. School of Occupational and Public Health, Faculty of Community Services, Ryerson University, Nov. 3.

Hirschorn, S., J. McKelvie, 2009. Deep Geologic Repository Development. Women in Nuclear Meeting, Nov. 12.

Hirschorn, S., M. Ben Belfadhel, 2009. The Long-term Management of Canada's Used Nuclear Fuel: A Geoscience Perspective. Queen's University Guest Lecture, Oct. 5.

Kwong, G.M. 2009. The Management of Canada's Used Nuclear Fuel and Carbon Steel Used Fuel Container. Carleton University, Apr. 3.

Kwong, G. 2009. Reversibility and Retrievability Scale – NWMO Used Fuel. NEA RWMC WG Meeting, Paris, France. June 4, 2009.

Kwong, G. 2009. The Role of Retrievability in Adaptive Phased Management. NEA RWMC WG Meeting. Washington D.C., U.S.A. December 2, 2009.

Russell, S., Patton, P. 2009. Long-term Management of Canada's Used Nuclear Fuel. Lakehead University Speaker Series, Mar. 17.

A.3 Ph.D. and M.Sc. Students

Ph.D. Theses

Normani, S. D. 2009. Paleoevolution of pore fluids in glaciated geologic settings. Doctor of Philosophy Thesis, University of Waterloo

NWMO awarded the following students industrial postgraduate scholarships in collaboration with the Natural Sciences and Engineering Research Council of Canada:

Andres, Heather. Anthropogenic Forcing of the Greenland Ice Sheet Mass Balance: Regional Climate Responses and Feedbacks, University of Toronto. Supervisor Dr. Dick Peltier.

Henkemans, Emily. Interaction between a continental ice sheet and groundwater, Kangerlussuaq, West Greenland. University of Waterloo. Supervisor Dr. Shaun Frape.

Makahnouk, Mike. Water/Rock Interaction Related to Mineralogy, Paleoclimate, and Long Term Rock Stability Studies, University of Waterloo. Supervisor Dr. Shaun Frape.

A.4 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

4DM Inc.
AECOM
AMEC-NSS
Alberta Research Council
Amphos21
Atomic Energy of Canada Ltd.
BJ Machine
Candesco Corporation
Chandler, N.
Columbia University (Dr. Leonardo Seeber and Dr. Klaus Jacob)
David P. Jackson & Associates Ltd.
Derek Martin Consulting Inc.
ECOMatters Inc.
Engineering Simulations Inc.
Enviros Consulting Ltd.
FSS Canada Consultants Inc.
G.R. Simmons & Associates Consulting Services Ltd.
Gascoyne GeoProjects Inc.
Geologic Survey of Canada
Golder Associates Ltd.
HydroGeoLogic Inc.
Integrity Corrosion Consulting Ltd.
Intera Engineering Ltd.
Jacob, Dr. Klaus
John Sims and Associates
Kinectrics Inc.
Lakehead University (Dr. B. Kjartanson)
Ma, Dr. Shutian
March Consulting Associates Inc.
McGill University (Dr. P. Selvadurai)
New Mexico Institute of Mining and Technology (Dr. Mark Person)
Nuclear Safety Solutions Limited
Queen’s University (Dr. K. Novakowski, Dr. Diederichs)
Quintessa Inc.
Royal Military College of Canada (Dr. G. Siemens)
RSRead Consulting Inc.
SENES Consultants Ltd.

Serco Technical and Assurance Services
SKB International Consultants
SNC Lavalin
SWRI
U.S. Geological Survey
Université Laval (Dr. R. Therrien)
University of Bern (Dr. Mazurek)
University of British Columbia (Dr. U. Mayer)
University of Calgary (Dr. Patrick Wu)
University of Manitoba (Dr. J. Blatz)
University of New Brunswick (Dr. T. Al, Dr. K. MacQuarrie)
University of Ontario Institute of Technology (Dr. B. Ikeda)
University of Toronto (Dr. R.C. Newman, Dr. P. Young, Dr. W. Peltier, Dr. B. Sherwood Lollar)
University of Waterloo (Dr. S. Frape, Dr. E. Sudicky, Dr. J. Sykes, Dr. S. Normani, Dr. Y. Yin)
University of Western Ontario (Dr. D. Shoesmith, Dr. G. Atkinson)

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2009

ABSTRACT

Title: **Technical Research and Development Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2008**
Report No.: **NWMO TR-2009-01**
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
Company: Nuclear Waste Management Organization
Date: March 2009

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.

ABSTRACT

Title: **POLARIS UNDERGROUND PROJECT AT SNO (P.U.P.S.) Year 3 Report**
Report No.: **NWMO TR-2009-02**
Author(s): Gail Atkinson and Nadia Kraeva
Company: University of Western Ontario
Date: December, 2009

Abstract
This report describes the 3-year PUPS (POLARIS Underground Project at Sudbury Neutrino Observatory) project and its findings. The main objective of PUPS was to conduct an experiment in 3-dimensional seismic monitoring at the Sudbury Neutrino Observatory (SNO) to address a range of scientific or engineering objectives related to seismic hazard of underground facilities.
The PUPS project has analyzed ground motions on the surface and underground for local, regional and teleseismic earthquake events and has shown the following:

1. Generally earthquake ground motions underground are lower in amplitude than those on the surface.
2. The relationship between underground and surface motions is complex, with the ratio of surface/underground motions being a frequency-dependent function that depends on the type of earthquake and the depth of the underground cavern.
3. Motions on the surface are amplified in specific frequency ranges due to the presence of surface waves in the signal.
4. For nearby shallow earthquakes, strong surface waves cause a peak amplification of surface motions (at about 2 Hz) relative to those underground that often exceed a factor of two.
5. For larger distant earthquakes, the surface waves cause amplification at longer periods which decrease in amplitude as the depth of the underground station increases.
6. At very low (0.1 Hz) and very high frequencies (>10 Hz), underground and surface motions are very similar in amplitudes.
7. In general, the potential for surface waves and the frequency range that they affect is dependent on the characteristics of the source (such as its depth) and the distance to the site.
8. Ground motions decay at a rate of approximately $R^{-1.3}$ in the first 20 to 30 km from the earthquake source (where R is distance). This supports the ground-motion prediction equations of Atkinson and Boore (2006), and implies that a mitigating factor in seismic hazard studies in Ontario is this relatively steep attenuation of wave amplitudes as we move away from an earthquake source.
9. Kappa values, which control the attenuation of motions at very high frequencies, are unexpected large (0.02 to 0.05) at both surface and underground SNO sites.

ABSTRACT

Title: **X-RAY RADIOGRAPHY TECHNIQUES FOR MEASURING DIFFUSIVE PROPERTIES OF SEDIMENTARY ROCKS**
Report No.: **NWMO-TR-2009-03**
Author(s): L.C. Cavé, T.A. Al and Y. Xiang
Company: University of New Brunswick
Date: February 2009

Abstract
Characterization of the diffusive properties of low permeability sedimentary rocks is an important component of the safety case for a deep geological repository (DGR) for used nuclear fuel, because diffusion is expected to be the dominant solute transport mechanism in this environment. In low permeability rocks, conventional laboratory tracer techniques for diffusion measurements typically involve experimental times of several weeks or months. Radiography offers the advantages of non-destructive analysis in that several time series measurements can be made on the same sample and with shorter experimental times because a steady-state condition is not required.

This report describes the development and testing of an X-ray radiography technique for characterizing and quantifying the concentration distribution of an iodide tracer solution in rock samples. The pore diffusion coefficient (D_p) for iodide in the rock can be estimated from the iodide concentration distribution by fitting an analytical solution of Fick's Second Law. Diffusion coefficients can be used in predictive models to estimate potential solute transport rates in porous media. The collection of X-ray radiograph images at successive time intervals also gives a valuable visual representation of the movement of tracer inside the rock, which can be used to enhance understanding of the diffusion process. X-ray absorption measurements on samples before and after saturation with iodide can also be used to determine the iodide accessible porosity (ϕ_I).

Initial testing of the radiography method has been conducted using archived drill core samples from the Ordovician-aged Queenston Formation shale and Cobourg Formation limestone, southern Ontario, Canada. Pore diffusion coefficients of $(4.8 \pm 2.5) \times 10^{-11}$ m^2/s (mean ± standard deviation) were measured for six Queenston Formation shale samples and $(2.6 \pm 1.0) \times 10^{-11}$ m^2/s for six samples of Cobourg Formation limestone. The results compare well with D_p data calculated from effective diffusion coefficients measured on adjacent rock samples using a conventional through-diffusion method, which average $(4.6 \pm 2.0) \times 10^{-11}$ m^2/s for shale and $(3.5 \pm 1.8) \times 10^{-11}$ m^2/s for limestone. Low porosity (0.01 to 0.03) and high matrix X-ray absorption are limiting factors that affect the sensitivity of the radiographic technique for the limestone samples because of poor signal to noise ratios. Low porosity and heterogeneous distribution of porosity at the scale of the samples (mm to cm) may also be responsible for the slightly poorer agreement between radiogaphy and through-diffusion results for this rock type.

Mean values of ϕ_I measured by radiography for 2 shale samples (0.060 ± 0.004) and 6 limestone samples (0.028 ± 0.005) were close to mean porosity measurements made on adjacent samples (15 shales and 7 limestones) by the independent water loss technique (0.062 ± 0.007 and 0.020 ± 0.008 for shales and limestones, respectively).

ABSTRACT

Title: **Reactive Transport Modelling in Fractured Rock – Redox Stability Study**
Report No.: **NWMO TR-2009-04**
Author(s): S.M. Spiessl[1], K.U. Mayer[1], K.T.B. MacQuarrie[2]
Company: [1]Department of Earth and Ocean Sciences, University of British Columbia
[2]Department of Civil Engineering, University of New Brunswick
Date: March 2009

Abstract
The Nuclear Waste Management Organization (NWMO) is responsible for implementing Adaptive Phased Management, the approach selected by the Government of Canada for long-term management of used nuclear fuel waste generated by Canadian nuclear reactors (NWMO 2005). The ultimate objective of Adaptive Phased Management is centralized containment and isolation in a suitable geological formation in either sedimentary or crystalline rock. In the crystalline rocks of the Canadian Shield, geochemical conditions are currently reducing at depths of 500 to 1000 m. Such reducing conditions are well suited for a deep geologic repository for used nuclear fuel. However, during future glacial periods, altered hydrologic conditions could potentially result in recharge of glacial melt water containing a relatively high concentration of dissolved oxygen (O_2).

In this study, the reactive transport code MIN3P is employed to investigate redox processes in fractured crystalline rock under the simplifying assumption of vertical groundwater flow to a depth of 500 m. The primary objectives of the research are to provide a greater understanding of the basic processes controlling the transport of O_2 and to identify the important parameters controlling oxygen ingress and the uncertainty associated with these parameters. Base case scenarios are developed that represent present-day and hypothetical glacial melt water recharge into a single fracture-matrix system and into a fracture zone. For the single fracture base case, which is constrained to the extent possible by parameter values characteristic of Canadian Shield rocks, oxygen diffusion into the rock matrix and consumption by reduced iron minerals (e.g. biotite) was found to limit the depth of dissolved oxygen migration to less than 15 m below the assumed zone of oxygenated groundwater during a simulated melt water production period of 10,000 years. For the fracture zone case, which is characterized by a significantly increased O_2-mass loading, the ingress of O_2 is limited to approximately 70 m below the assumed zone of oxygenated groundwater. The results of the uncertainty analyses indicate that for the single fracture case, the most influential factors controlling O_2 ingress are flow velocity in the fracture, fracture aperture, and biotite reaction rate. The most important parameters for the fracture zone simulations are flow velocity, pO_2 in the recharge water, biotite reaction rate, and to a lesser degree the abundance and reactivity of chlorite in the fracture zone, and the fracture zone width. These parameters should therefore be reasonably well constrained if site-specific modelling is to be undertaken.

ABSTRACT

Title: **SEISMIC ACTIVITY IN THE NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD - ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 - DECEMBER 31, 2008**
Report No.: **NWMO TR-2009-05**
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: March 2009

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 on-going 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 2008.

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 2008.

During this twelve-month period 114 earthquakes were located. Their magnitude ranged from 0.1 m_L to 3.2 m_N. The largest events included a m_N 3.2 in the Atikokan region, a m_N 3.0 in the Kapuskasing-Cochrane region and a 2.9 m_N north of Red Lake, Ontario. The most westerly event in the area being studied was a m_N 2.8 event located just west of Deer Lake, ON. The 114 events located in 2008 compares with 68 events in 2007, 83 events in 2006, 103 events in 2005, and 79 events in 2004.

ABSTRACT

Title: **Theory Manual for the Steel Corrosion Model Version 1.0**
Report No.: **NWMO TR-2009-07**
Author(s): Fraser King[1] and Miroslav Kolar[2]
Company: [1]Integrity Corrosion Consulting Ltd. [2]LS Computing Ltd.
Date: March 2009

Abstract
A model for the prediction of the anaerobic corrosion behaviour of carbon steel used fuel containers in a deep geological repository in sedimentary host rock in Canada is described. The model is termed the Steel Corrosion Model Version 1.0 (SCM V1.0). The model is designed to predict not only the corrosion behaviour of the container but also the impacts of corrosion products, specifically dissolved ferrous species and hydrogen, on the other barriers in the system, particularly the bentonite or bentonite/sand buffer. This theory manual describes both the conceptual mechanistic model and the mathematical model used for predictions.

The conceptual model is based on a reaction scheme that includes a total of 13 species, namely: a dissolved ferrous-chloro complex $FeCl^+(aq)$, a dissolved ferrous-carbonate complex ion $Fe(CO_3)_2^{2-}(aq)$, dissolved ferrous-hydroxy ion $FeOH^+(aq)$, dissolved hydrogen $H_2(aq)$, the bicarbonate ion $HCO_3^-(aq)$, the chloride ion $Cl^-(aq)$, solid ferrous hydroxide $Fe(OH)_2(s)$, magnetite $Fe_3O_4(s)$, siderite or iron carbonate $FeCO_3(s)$, adsorbed ferrous species $Fe(II)_{ADS}$, iron-altered clay Fe(clay), calcite $CaCO_3(s)$, and hydrogen gas $H_2(g)$. These species participate in a number of interfacial electrochemical reactions, precipitation and dissolution processes, adsorption and desorption of cations on bentonite clay, mass transport towards and away from the container, alteration of the bentonite clay by reaction with Fe(II), gas generation and transport, and partitioning between aqueous and gaseous phases.

Other features of the model include a detailed analysis of corrosion product film formation processes, as part of which the time-dependent thickness and porosity of the film is predicted. The effects of repository saturation on mass transport and on the rates of interfacial and other processes are considered. Hydrogen generation and transport is also treated in the model, as is the alteration of clay by reaction with dissolved Fe(II) species.

The mathematical model is based on a series of 15 one-dimensional reaction-transport equations, one each for the 13 chemical species, one for the porosity of the corrosion product film, and one for temperature. These equations are solved subject to various boundary and initial conditions within a spatial grid designed to represent the geometry of the repository. The most important of these boundary conditions are the electrochemical expressions that describe the rates of the interfacial corrosion reactions. By using the reactions as boundary conditions for the solution of the mass-balance equations, the model is able to not only couple the corrosion behaviour of the container to the evolution of the repository environment, but also to predict the time dependence of the corrosion potential and corrosion rate through the use of mixed-potential theory.

The theory manual describes the conceptual model and reaction scheme in some detail, along with a discussion of the various underlying assumptions in the model. The mathematical model is also described, including the 15 reaction-transport equations, the initial and boundary conditions, the spatial grid, and the finite-difference technique used for the numerical solution.

ABSTRACT

Title: **Development of Delayed Hydride Cracking Test Apparatus and Commissioning Tests for CANDU Fuel Bundle Assembly Welds**
Report No.: **NWMO TR-2009-08**
Author(s): Gordon K. Shek and Bogdan S. Wasiluk
Company: Kinectrics Inc.
Date: October 2009

Abstract
A test apparatus was developed for performing delayed hydride cracking (DHC) tests on the assembly fuel element welds of a fuel bundle. Experimental procedures to measure the stress intensity factor (K_{IH}) for DHC initiation from the weld and the crack velocity (DHCV) were developed. A finite-element stress analysis methodology was developed to calculate the applied stress intensity factor at the weld discontinuity under the loading conditions of the experiment. Several K_{IH} and DHCV tests were successfully performed on the fuel element welds from unirradiated fuel bundles.

The following can be concluded:

(1) A test apparatus was developed and fabricated capable of measuring DHC properties such as K_{IH} and DHCV of the endplate/endcap welds of unirradiated fuel bundles.

(2) Test procedures to obtain K_{IH} and DHCV properties of the endplate/endcap welds were established.

(3) The methodology to determine the applied stress intensity factor at the weld discontinuity under the loading conditions of the DHC tests was developed.

(4) Four of the five samples tested in this program had K_{IH} values ranging from 7.6 to 8.3 MPa√m. The other sample had a K_{IH} value of 13.6 MPa√m, probably due to a difference in crack depth and the shape of the weld. The cracking mechanism was confirmed to be DHC by metallographic examination. Formation of hydrides at the crack tip was confirmed through SEM examination. Further, the response of the cracking process to temperature and the loading cycle was consistent with DHC behaviour.

(5) DHCV at 150°C of the endplate/endcap welds was found to increase after a heat-tinting cycle. DHCV ranged from 5.7 x 10^{-10} m/sec to 2.1 x 10^{-9} m/sec prior to heat-tinting and increased to 1.3 x 10^{-9} m/sec to 5.5 x 10^{-9} m/sec after the heat-tinting.

ABSTRACT

Title: **State-of-the-Science Review of the Stress Field during a Glacial Cycle and Glacially Induced Faulting**
Report No.: **NWMO TR-2009-09**
Author(s): Patrick Wu
Company: University of Calgary
Date: December 2009

Abstract
Glaciation and deglaciation cycles are known to have an influence on the regional state of stress, fault stability and the generation of earthquakes that may affect the safety of nuclear waste underground repositories. This report reviews the scientific background related to glaciers, Ice Ages and the response of the Earth to glacial cycles. It also summarizes current knowledge and understanding of the influence of glacial cycles on the evolution of fault stability.

To model the spatio-temporal variation of stress and fault stability, the stresses induced from glacial loading, including those from bending of the lithosphere and relaxation of the mantle are superposed on the overburden stress, pore fluid pressure and ambient tectonic stresses to give the total stress. The effect of stress changes associated with sedimentation and erosion processes and shear induced by glacier flow are also considered and found to be relatively unimportant. Various rock failure criteria including the changes in fault stability margin (δFSM) as developed by Wu and Hasagawa (1996) from Mohr-Coulomb failure criteria are reviewed and the assumption of virtual faults and optimal orientation are also discussed.

The spatio-temporal variation of δFSM in Laurentide, Fennoscandia, and Scotland were studied. For loads of large horizontal extent (e.g. Laurentide ice sheet), fault instability is suppressed by the weight of the load. However, this is not true for small isolated ice caps since the effect of stress amplification becomes important. The effects of tectonic stress and overburden, material properties, compressibility, mantle rheology and lithospheric ductile zones are also studied. It is found that a thrust background stress regime is able to explain many of the observed data in Laurentia and Fennoscandia. The size of the ice sheet and its deglaciation history are found to have large effects on the onset timing of earthquakes inside and outside the ice margin. Mantle rheology has large effects on the onset time of earthquakes and the amplitude of δFSM outside the ice margin, but has little effect on the onset timing and mode of failure within the ice margin. However, mantle viscosity has a large effect on the rate of change in δFSM within the ice margin for the next few thousand years. A vertical ductile zone within the lithosphere is found to concentrate the strain rate and δFSM near the ductile zone inside the ice margin.

The virtual fault assumption is also reviewed. Results from simple models of slip evolution of a single fault plane confirm that faults can become stabilized when loaded by an ice sheet of large enough thickness. There is slip acceleration after the onset of deglaciation and the computed magnitude of slip is found to be comparable to that observed in Fennoscandia.

Finally, the limitations of the above models are discussed. These limitations indicate possible directions of future research.

ABSTRACT

Title:	**Hydrogeochemistry of groundwaters at and below the base of the permafrost at Lupin: Report of Phase III**
Report No.:	**NWMO TR-2009-10**
Author(s):	R.L. Stotler[1], S.K. Frape[1], T. Ruskeeniemi[2], L. Ahonen[2], M. Paananen[2] M.Y.Hobbs[3], K. Lambie[1], and M. Zhang[1]
Company:	[1]University of Waterloo, [2]Geological Survey of Finland, [3]Nuclear Waste Management Organization
Date:	June 2009

Abstract

Over the long time frames for which a Safety Case for a deep geologic repository for used nuclear fuel must assess repository performance, glacial and peri-glacial conditions may influence the thermal, hydraulic and mechanical boundary conditions at repository depth. To improve scientific understanding of the influence of climatic evolution on groundwater flow system dynamics in crystalline terrain, the international PERMAFROST project was initiated in 2001. Field research is conducted at the Lupin Mine in Nunavut Canada, situated in an area of continuous permafrost that extends to a depth of 500 m. Phase III of the project is described in this report, and was focused on the collection of representative geochemical and hydraulic information to further describe the groundwater flow system and permafrost geometry.

The results of the initial hydraulic investigations show that the hydraulic conductivity within the first 350 m of bedrock east from the mine is controlled by an interconnected network of fractures, rather than by pervasive planar fault-type structures (fracture-dominated flow). The hydraulic field is heterogeneous; closely spaced research boreholes have hydraulic head differences of up to 160 m, suggesting that either the boreholes are not connected or are only poorly connected. Pressure monitoring at deeper levels within the mine (890 m and 1130 m level) indicated that the water table is located approximately 620 m below surface, suggesting the presence of approximately 100 m of unsaturated zone below the permafrost.

Groundwaters from within the permafrost are typically Na-Cl or Na-Cl-SO_4 type, with highly variable SO_4 concentrations and high NO_3 concentrations (400-2600 mg/L). Geochemical data indicates that much of the dissolved load in the permafrost waters has come from the use of salt for the creation of brine for work in the permafrost areas during mine operation. This interpretation of permafrost waters impacted by mining operations is further supported by tritium and stable isotopic data ($\delta^{18}O$, $\delta^{2}H$, $\delta^{15}N$).

Deep groundwaters are Na-Ca-Cl or Ca-Na-Cl types with a wide range of TDS values, from 2 to 36 g/L. Gases associated with the deep groundwaters are predominantly methane, with ethane and propane as minor constituents. Comparison to other gases from shield environments suggests that the gases associated with the deep groundwater systems have a thermogenic origin, although there may also be a small biogenic component. The thermogenic component of the gases was most likely derived during amphibolite facies metamorphism (low pressure, high temperature) of the original sediments, suggesting that the gases, and by association the matrix fluids and most of the saline groundwaters, are hundreds of millions to billions of years old. This is further supported by ^{36}Cl analysis, which suggests the Cl^- in the subpermafrost system is older than the limit of the ^{36}Cl dating technique (0.5 to 1 million years). A preliminary conceptual model for the Lupin site is presented here.

ABSTRACT

Title: **High Lake Permafrost Comparison Site: Permafrost Phase IV**
Report No.: **NWMO TR-2009-11**
Author(s): Brian Holden[1], Randy L. Stotler[1], Shaun K. Frape[1], Timo Ruskeeniemi[2], Matti Talikka[2] and Barry M. Freifeld[3]
Company: [1]University of Waterloo
[2]Geological Survey of Finland
[3]Lawrence Berkeley National Laboratory
Date: July 2009

Abstract

The aim of the PERMAFROST project (a collaboration with the Geologic Survey of Finland (GTK), POSIVA, AKB, NASA, and OPG) is to further advance the scientific understanding of permafrost and its role in influencing flow system evolution over geologic timescales. The first three phases of the PERMAFROST project were conducted at the Lupin Mine site in Nunavut Canada. Results of Phase IV, conducted at High Lake, Nunavut, are described here.

Phase IV of the project aimed to obtain fluid samples from beneath a permafrost layer that has not been impacted by sub-permafrost mining activity. A borehole drilled previously at the site (borehole HLW 03-28) was extended and a deep borehole assembly (DBA) with a modified u-tube water extraction device was utilized to transport groundwater from below the permafrost to the surface for collection and analysis. Freezing of the borehole prevented collection of some planned samples, and required the use of drilling brine. Samples were collected from water bailed from the borehole and purged from the U-tube, and the chemical and isotopic compositions of these samples were determined. The DBA allowed temperature and pressure measurements to be obtained and hydraulic conductivity to be estimated (2×10^{-11} m/s). Surface and talik water samples were collected and chemically and isotopically characterized. The crush and leach technique was used to extract fluids from sections of core selected from throughout the length of the borehole column. For conservative ions, such as Cl and Br, compositions measured using crush and leach are likely representative of matrix fluid compositions. Chemical and isotopic analysis of waters collected during borehole bailing (2006) and U-tube purging (2007) suggest that the samples may be strongly impacted by drill brine contamination. This is further supported by tracer analysis (uranine and tritium) of the U-tube samples, which gives quantitative estimates of 37% to 100% drill brine contamination in the U-tube samples. However, even with the significant influence of drill brine on these samples, chemical and isotopic results can be compared to data collected in Phases I to III of the PERMAFROST project, and similarities between the High Lake site and the Lupin site are observed. In addition, trace amounts of hydrocarbon gases were detected and analyzed from two of the U-tube samples, and the ratio of methane to ethane and propane suggests the gases were not produced bacteriogenically. Carbon and oxygen stable isotope data of fracture calcites at High Lake are similar to previously reported fracture calcite isotopic values for Slave Province.

While samples collected in this study were impacted by drill brine contamination, the study demonstrates the potential for the deep borehole assembly approach to provide good quality chemical samples, provided a method for preventing the sample lines from freezing can be developed.

ABSTRACT

Title: **Technical Summary of the Safety Aspects of the Deep Geological Repository Concept for Used Nuclear Fuel**
Report No.: **NWMO-TR-2009-12**
Author(s): F. Garisto, T. Kempe and P. Gierszewski
Company: Nuclear Waste Management Organization
Date: September 2009

Abstract
This report brings together a technical summary of information on the safety of a deep geological repository for used nuclear fuel. It explains why the repository concept is expected to be safe. The report is non-site-specific; it considers alternative geologic settings, specifically both the Canadian Shield and sedimentary rock formations; and encompasses several design concepts.

The key reasons supporting the safety of the deep geological repository concept are:

1. A geological repository uses multiple barriers that include the waste form, container, sealing materials, and the host rock.
2. The host rock would be stable and predictable over long periods of time.
3. The low-permeable host rock would ensure that the waters in the deep rock are isolated and do not readily mix with surface waters.
4. The deep geological repository system would maintain a chemical and hydrological environment that is favourable to the stability and performance of the repository.
5. Natural analogues provide evidence that engineered barrier materials are stable for very long times under similar deep geologic conditions.
6. The depth of the repository would be such that future inadvertent human intrusion into the closed repository would be very unlikely.
7. International progress on repository implementation gives assurance that geological disposal is a sound technical solution and provides practical experience.
8. Safety assessment case studies indicate that any impacts are likely to be well below recommended dose constraints and natural background dose rates.
9. A geological repository can be built and operated safely using proven technologies.
10. The radionuclides in the used fuel decay with time.
11. The repository site will be monitored to confirm repository system performance.

The safety of any proposed repository site would be tested through a rigorous regulatory system and international peer review of the safety case. The Canadian program continues to develop the scientific tools and understanding that will be applied to test the suitability of any candidate site.

ABSTRACT

Title:	**Feasibility of Using Geoscientific Criteria for Early Screening of Large Geographic Areas that would be Unsuitable for Safely Hosting a Deep Geological Repository**
Report No.:	**NWMO TR-2009-13**
Author(s):	R.E.J. Leech, T.L. Wlodarczyk, S. Davies, M. Lee
Company:	AECOM Canada Ltd.
Date:	May 2009

Abstract

The Nuclear Waste Management Organization (NWMO) is responsible for implementing Adaptive Phased Management (APM), Canada's plan for the long-term care of the used nuclear fuel produced by Canada's nuclear reactors. The end point of APM is long-term containment and isolation of used nuclear fuel in a deep geological repository constructed in a suitable rock formation at a depth of approximately 500 m.

One of the major tasks with regard to implementing APM is to collaboratively develop the process that will be used for seeking an informed and willing community to host the deep geological repository. For fairness, the siting process will be focused in the four provinces directly involved in the nuclear fuel cycle: Saskatchewan, Ontario, Québec and New Brunswick. In order to inform the siting process, the NWMO identified the need to review the available geoscientific information in the four nuclear provinces as well as the scope and application of geoscientific factors at early stages in a siting process for a geological repository, based on international guidance, Canadian regulatory requirements and the experience of other countries.

In this context, NWMO retained AECOM Canada Limited (AECOM) to undertake the following: i) review geoscientific factors that need to be considered to ensure the safety of a geological repository; and ii) assess the feasibility and practicality of using proposed geoscientific exclusion criteria for early identification of large geographic areas within the four nuclear provinces that would be unsuitable for safely hosting a deep geological repository without the need for further field investigation.

This report reviewed the geoscientific characteristics of the four nuclear provinces as well as the geoscientific factors would be considered to ensure the safety of a deep geological repository. The safety functions considered include the ability of the repository to safely contain and isolate used nuclear fuel, the long-term stability of the site, the ability to easily characterize the site, the safe construction, operation and closure of the repository and the potential for human intrusion in the long term. The geoscientific characteristics and factors reviewed were grouped under geology, geomechanics, seismicity, hydrogeology, hydrogeochemistry and the potential for economically exploitable natural resources.

The assessment of whether the geoscientific factors considered could be used to exclude large areas of the four nuclear provinces early in the siting process highlighted two main challenges. First, most of the geoscientific factors that need to be considered require site specific information at depth which is typically lacking at early stages in the siting process. The other challenge is associated with the large geographic extent of the four nuclear provinces (3,300,000 km^2) compared to the typical repository scale at which site specific geoscientific information is needed (~6 km^2). After reviewing the international literature and the available geoscientific information from the four provinces, it is concluded that:

It is not practical to exclude large areas of the four nuclear provinces early in the siting process (pre-screening) based on the geoscientific factors identified herein. However, some of the geoscientific factors may be used as exclusion factors at later stages of the site evaluation process as more local scale and site specific information becomes available such as during screening studies, feasibility studies and detailed field investigations.

The findings of this report are consistent with international experience and the outcome of general siting studies conducted in other countries.

ABSTRACT

Title: **Transport of Used Nuclear Fuel – A Summary of Canadian and International Experience**
Report No.: **NWMO TR-2009-14**
Author(s): U. Stahmer
Company: Nuclear Waste Management Organization
Date: April 2009

Abstract
Each day, thousands of radioactive material shipments are made by road, rail, water and air around the world. Of particular interest is the transport of used nuclear fuel, a by-product of electricity production at nuclear generating stations. Used nuclear fuel is classified as both radioactive material and hazardous waste.

This report provides a brief summary of Canadian and international experiences in the transportation of used nuclear fuel. Also discussed is Canada's governing regulatory framework for transportation of dangerous goods and hazardous waste.

In particular, this report provides a summary of:

1. Canadian and international experience in the transport of used nuclear fuel;
2. the current regulatory framework which governs the transport of hazardous waste, and in particular, used nuclear fuel within Canada;
3. waste volumes transported annually;
4. the types of packages used to transport used nuclear fuel; and
5. the regulatory tests that transportation packages must meet.

The transportation of used nuclear fuel has been and continues to be conducted safely in Canada and internationally. In over 45 years of used nuclear fuel transport, not a single incident or accident has resulted in significant radiological damage to people or the environment. In all, over 80,000 tonnes of used nuclear fuel have been transported around the world to date. The industry's excellent safety record is a direct result of robust international standards which have been adopted and implemented by national regulatory programs.

ABSTRACT

Title: **Preliminary Evaluation of the Ultracentrifugation Method for Extraction of Pore Fluids from Sedimentary Rocks**
Report No.: **NWMO TR-2009-15**
Author(s): M. Gascoyne[1] and M. Hobbs[2]
Company: [1]Gascoyne GeoProjects Inc. [2*]Nuclear Waste Management Organization (*now at Institute for Geological Sciences, University of Bern, Switzerland)
Date: December 2009

Abstract
The compositions of pore fluids within deep sedimentary rock formations are required for near-field performance and safety assessment calculations for deep geologic repositories and for models involving groundwater transport or evolution. Few direct methods are currently available for the extraction of pore fluids from low permeability sedimentary formations. In the current study, the ultracentrifugation technique was applied to extract pore fluids directly from argillaceous limestones of the Cobourg Formation.

The argillaceous limestone core samples used in this study were obtained from a borehole drilled in August, 2006 at the St. Mary's Cement property near Bowmanville in southwestern Ontario. The cores were vacuum-sealed within 30 minutes of core recovery and stored in a refrigerator at 4°C until analysis. Pore fluid was extracted by spinning core pieces at a rate of 15,000 rpm under controlled conditions of temperature and pressure, according to a protocol originally developed for volcanic tuffs by the U.S. Geological Survey and adapted in this study for application to sedimentary rocks. Despite the very low water contents determined for the limestones (0.3 to 2.5 wt.%), between 0.03 and 0.75 g of pore fluid were extracted using ultracentrifugation from one subsample of a core taken at a depth of 50.09 m and from 5 subsamples of a core taken at 73.86 m. Relative to the total water available in the sample as determined from the gravimetric water content, the portion of fluid extracted from the samples ranged from 0.6 to 6.8%. The pore fluid yields are much lower than those obtained in previous studies where centrifugation was applied to volcanic tuffs (23 to 46%) or to a chalk formation (40 to 95%) and likely reflects the lower porosity of the argillaceous limestones and/or lower connectivity between pores.

The total dissolved solids (TDS) content of pore fluids extracted from 5 subsamples of one core from a depth of 73.86 m ranged from 4,400 to 52,500 mg/L. Pore fluid extracted from a subsample of core from a depth of 50.09m had an intermediate TDS value of 10,100 mg/L. The concentrations of both Ca^{2+} and Na^{+} were observed to increase with increasing Cl^{-} concentration (the Na/Ca ratio also increased), whereas the Br/Cl ratio decreased. In two sequential extractions on a single subsample of core, the quantity of fluid extracted after 4 hours of spinning in the second extraction was more than twice that extracted during the first, 2 hour extraction step. Decreases in the major ion concentrations by factors between 0.7 and 3.4 were observed between the two extraction steps; well beyond the analytical uncertainty of ±10%. This observation suggests that the variations observed in pore fluid composition do not reflect in-situ variations, but rather may be the result of changes in pore fluid composition that occurred prior to (e.g. by evaporation) or during ultracentrifugation as the result of an ion filtration process. It is not possible to conclude whether one or both of these processes affected the extracted pore fluid compositions. Future studies of water content changes during core transport and storage could be used to explore the importance of evaporation. Additionally, multiple sequential extractions from single core samples and comparison with pore fluids

extracted using an independent method and/or groundwaters sampled in close proximity could be used to further examine how representative the extracted pore fluids are of in-situ pore fluids.

ABSTRACT

Title: **Sorption in Highly Saline Solutions – State of the Science Review**
Report No.: **NWMO TR-2009-18**
Author(s): Peter Vilks
Company: Atomic Energy of Canada Limited
Date: July 2009

Abstract
The sorption of radionuclides onto mineral surfaces within the geosphere, and on the materials making up the engineered barriers of a deep geologic repository is an important mechanism for slowing the transport of radionuclides to the surface environment. A Canadian sorption database for the post closure assessment of a hypothetical repository in the Canadian Shield with groundwater compositions having up to 11 g/L TDS was finalized in 1996. With the Canadian Government's selection of the Adaptive Phased Management approach for the long-term management of Canada's used nuclear fuel, both crystalline and sedimentary rock formations are under consideration as potential host formations (NWMO, 2005). Sedimentary rocks in Canada, for example in the Michigan basin, have been observed to contain Na-Ca-Cl and Ca-Na-Cl brines with TDS concentrations reaching 300 g/L. Deep groundwaters in the Canadian shield may also contain brines with TDS values up to 400 g/L. Therefore, there is a need to establish an understanding of how brine solutions affect sorption on sedimentary and crystalline rocks. The purpose of this report is to describe the results of a literature survey to evaluate the state-of-science knowledge of sorption processes and their contribution to mass transport, with a particular focus on processes that would occur in high salinity water. The report identifies data gaps that need to be addressed for understanding sorption in brine solutions and proposes an experimental strategy to address these gaps.

The international literature contains data for radionuclide sorption on sedimentary formations at the Gorleben site, Germany, for a range of groundwaters that include NaCl brines with TDS as high as 159 g/L. Actinide sorption on dolomite in the presence of NaCl brines with TDS up to 338 g/L has been described for the WIPP site, New Mexico. Information from these programs, combined with our current understanding of sorption mechanisms indicates that in brine solutions the mass action effects of Na^{+} and Ca^{2+} will significantly reduce or eliminate the sorption of elements such as Cs^{+}, Sr^{2+} and Ra^{2+} that are sorbed by coulombic attraction. Elements with a strong tendency to hydrolyse at pH values above 6 will be sorbed by surface complexation with minimal effects from TDS. Although this information provides valuable background knowledge, existing sorption databases can only be adapted to high salinity solutions after one has acquired an understanding of sorption processes in Na-Ca-Cl brine solutions with Canadian sedimentary and crystalline rocks. To address this need a two-stage program of sorption experiments has been proposed, starting with sedimentary rocks and eventually including crystalline rocks. Following the approach used to establish international sorption databases, the program proposes the initiation of "in-house" experiments using Canadian sedimentary rocks, and a range of brine compositions. The experimental program includes batch experiments to address sorption specific issues, and dynamic transport experiments designed to relate sorption processes to mass transport. The first stage would develop experimental protocols and collect scoping data. Stage 2 would build on the understanding gained in the first stage to improve the understanding of sorption processes and to develop predictive abilities through modelling efforts.

ABSTRACT

Title: **Thermal, Hydraulic and Mechanical Properties of Sealing Materials**
Report No.: **NWMO TR-2009-20**
Author(s): A. Man, J.B. Martino
Company: Atomic Energy of Canada Limited
Date: December 2009

Abstract
A large amount of work has been invested in developing an understating of the properties of materials used in engineered barrier systems for nuclear used fuel isolation in Canada and internationally. Clay based sealing materials have been designated by function and material. The proposed clay based sealing materials for use in Canada include: Light Backfill (LBF), Dense Backfill (DBF), Gapfill (GF) bentonite-sand buffer (BSB) and highly compacted bentonite (HCB). Cement based material is primarily designated as concrete and specifically low alkalinity concrete but cement based materials may also be used in grouting applications. Properties and behaviour of these materials are required to evaluate and model the performance of the overall repository sealing system.

The known properties and behaviour of these materials are summarized from various programs. As all natural materials vary, the details of the materials are identified when available. Not all properties of these materials have been determined and these are identified as knowledge gaps to guide future material testing programs.

ABSTRACT

Title: **Used Nuclear Fuel Inventory and Transportation Estimates**
Report No.: **NWMO TR-2009-21**
Author(s): U. Stahmer
Company: Nuclear Waste Management Organization
Date: August 2009

Abstract
This report provides future fuel inventory and transportation estimates to serve as a framework for conceptual design and cost estimating studies and to develop the capability to review transportation options to a used-fuel long-term management facility. Fuel inventories for future scenarios of 3.6 million used nuclear fuel bundles (base case) and 7.2 million used nuclear fuel bundles (alternate case) are presented.

Assuming all road transport, approximately 18,600 shipments are required to transport 3.6 million fuel bundles to the long-term management facility over a 30 year transportation program and approximately 37,500 shipments are required to transport 7.2 million fuel bundles over a 60 year transportation program. This equates to approximately 630 shipments annually or 53 shipments per month.

The used nuclear fuel scenarios provided in this report have been constructed to provide a framework for conceptual design, cost estimating and operational planning only. These scenarios may differ from the plans of the reactor operators. Operation of the reactors, including decisions on refurbishment, would be subject to future decisions of the individual reactor operators.

ABSTRACT

Title: **Review of Borehole Based Geophysical Site Evaluation Tools and Techniques**
Report No.: **NWMO TR-2009-25**
Author(s): M.E. Monier-Williams[1], R.K. Davis[1], F.L. Paillet[2], R.M. Turpening[3], S.J.Y. Sol[1] and G.W. Schneider[1]
Company: [1] Golder Associates
[2] University of Arkansas
[3] Michigan Technical University
Date: November, 2009

Abstract

This report presents a discussion of borehole geophysical tools and techniques that could be applicable to the characterization of deep geological repository candidate sites. The techniques considered include wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and NMR logs), flow logging tools (impeller, heat pulse, electromagnetic, and fluid tracking), seismic methods (sonic and full waveform, tomography, reflection and VSP), borehole radar, borehole TDEM and cross-hole EM. The report provides guidance on the benefits that specific techniques may provide along with some constraints. Borehole geophysical techniques are heavily reliant on technology and as such, techniques will evolve and improve during the life span of a repository investigation.

Typical borehole geophysical applications are presented in this report, including the determination of lithology and stratigraphy, physical properties, rock structure and hydrogeologic properties, as well as in situ stress investigations, and well inspections. Nine case histories are presented and discussed, including crystalline and sedimentary rock environments from project sites in Europe and North America. The project sites presented include nuclear repository sites, underground test sites and heavy civil works.

Borehole geophysics has played an integral part in the characterization of both sedimentary and crystalline rock sites in every nuclear repository program. Borehole geophysical data are one of the primary inputs to the development of the site geosphere model. Virtually all borehole geophysical tools were found to be applicable to both sedimentary and crystalline rocks, although the importance of one tool versus the other does vary with the application.

Canada is very well positioned to apply borehole-based geophysical methods in these types of geoscientific and ground engineering studies. There are a number of well established consulting and service provider companies with the expertise and equipment inventory to complete these types of surveys.

ABSTRACT

Title: **Bentonite and Latex Colloid Migration Experiments in a Granite Fracture on a Metre Scale to Evaluate Effects of Particle Size and Flow Velocity**
Report No.: **NWMO TR-2009-26**
Author(s): Peter Vilks and Neil H. Miller
Company: Atomic Energy of Canada Limited
Date: November 2009

Abstract

One of the objectives of SKB's Colloid Dipole Project was to evaluate the potential of bentonite colloids to facilitate radionuclide transport. The field scale experiment undertaken at the Äspö TRUE-1 site was to use latex spheres as a proxy for bentonite colloids, To support this project, laboratory scale colloid migration experiments, using both bentonite and latex colloids, were performed in the Quarried Block (QB) sample, a 1m x 1m x 0.7 m block of granite containing a single, well characterized, variable aperture fracture. The main purpose of this laboratory program was to improve on the understanding of physical retardation processes that effect colloid mobility, and to provide additional information that could not be obtained at the field-scale such as bentonite versus latex colloid transport, particularly at low flow rates and different water compositions.

The purpose of this report is to present the results of the experimental program performed in 2007 that included (1) performing experiments with latex colloids in saline water, (2) exploring the effects of particle size on bentonite and latex colloid transport, (3) providing additional colloid transport data, for longer distances and low velocities, and (4) characterizing colloid deposition on fracture surfaces by post-test analysis.

Latex spheres, which are almost perfectly spherical and available as monodisperse (single-sized) suspensions, provide a useful tool for identifying the effects of particle size, structure and surface charge density on colloid transport. Experimental results showed that the transport behaviour of latex spheres in a natural fracture was consistent with filtration theory in which particle size determined the probability of particle interceptions with fracture surfaces or stagnant zones. Unlike bentonite colloids, latex colloids were more mobile in saline water, with migration properties influenced by the size of their flocs. In dilute water and under low flow experimental conditions, the prolonged residence times resulted in a tendency for bentonite and latex colloids to become fixed within the fracture system.

The results of the laboratory scale colloid migration experiments confirm that the conditions that limit colloid transport are typical of those found at depths and in rock settings that are proposed for deep geological repositories. These include the high ionic strength of brackish or saline water in which colloid stability in suspension is reduced, low groundwater flow velocities, and transport paths exhibiting fracture aperture heterogeneity and surface roughness that promote colloid entrapment and retention. The results also show that some colloid transport may occur under high flow rates and in waters with low ionic strength and neutral pH. However, even under dilute conditions, colloid transport from a deep geological repository system would tend to be limited by the reduced number of fractures, the inherent complexity of these pathways and lower porosity.

ABSTRACT

Title: **Alpha, Beta and Gamma Dose Rates in Water in Contact with Used CANDU Fuel**
Report No.: **NWMO TR-2009-27**
Author(s): F. Garisto[1], D.H. Barber[2], E. Chen[2], A. Inglot[2] and C.A. Morrison[2]
Company: [1]Nuclear Waste Management Organization, [2]AMEC NSS
Date: November 2009

Abstract
The Canadian concept for a geological repository for used fuel is based on multiple barriers, including the used UO_2 fuel itself. In the event of failure of the fuel container, groundwater would enter the container and contact the fuel, after the Zircaloy cladding is breached. Since more than 95% of the radionuclide inventory in used fuel is trapped within the fuel grains, the long-term release of radionuclides from the fuel is controlled by the dissolution of the used fuel.

Uranium dioxide has a low solubility under the reducing conditions expected in a deep geological repository and thus dissolves very slowly under such conditions. However, the radiolysis of groundwater, caused by the radiation emitted by used fuel, generates oxidants (e.g., H_2O_2) that can react with the fuel and dissolve it. Thus, the rate of dissolution of the fuel in a failed container is expected to be controlled by the rate of generation of oxidants by radiolysis of groundwater, until the radiation fields have decayed to sufficiently low levels. Consequently, it is important to have good estimates of the alpha, beta and gamma dose rates near the fuel surface.

The purpose of this report is to document the calculation of the alpha, beta and gamma dose rates in water in contact with a used fuel bundle, given the radionuclide inventories in used fuel. These dose rates are provided as a function of time for decay times from 10 to 10^7 years after discharge.

Based on the work described in this report the following additional conclusions can be made:

1. The appropriate value of the relative stopping power of alpha particles for water relative to uranium dioxide is 3.25.
2. The beta energy emitted by fuel is generated mainly by fission products for decay times up to about 200 years. The contribution from beta decay of the actinides and their progeny becomes significant after 200 years and is dominant for decay times greater than 300 years. However, by this time, the beta dose rate is much smaller than the alpha dose rate.
3. For gamma radiation, the F-factor is defined as the ratio of the gamma dose rate in water near a fuel bundle in a used fuel container to the corresponding dose rate from a single bundle in an infinite pool of water. The weighted average F-factors for the reference container ranged from 1.22 to 1.38, depending on the decay time. A value of 1.4 is recommended for safety assessment calculations.

ABSTRACT

Title: **Application of Numerical Modelling in Choosing Container Spacing, Placement-Room Spacing and Placement-Room Shape for a Deep Geological Repository Using the In-Floor Borehole Placement Method**
Report No.: **NWMO TR-2009-28**
Author(s): R. Guo
Company: Atomic Energy of Canada Limited
Date: October 2009

Abstract
A series of three-dimensional thermal transient and thermal-mechanical (T-M) stress analyses was performed on a deep geological repository (DGR) for used CANDU fuel using the in-floor borehole placement method. The DGR is assumed to be located at a depth of 500 m in crystalline rock. Near-field thermal analyses were carried out to develop a number of thermally acceptable repository layouts. Among these repository layouts, a specific repository layout design with a container spacing of 4.2 m and a placement room-spacing of 40 m was selected for further excavation stability analyses. This specific repository layout design requires the shortest total length of placement rooms and access tunnels.

A coupled near-field T-M model was conducted for the first 1,000 years after placement of the used fuel in a DGR. Excavation-induced mechanical stresses in the rock around the placement room and the placement borehole were studied for circular and elliptical shaped placement-rooms. The stability of the rock mass was evaluated using the Hoek and Brown empirical failure criterion. Excavation of placement room would not cause any significant failure in the rock surrounding the placement room. However, drilling the in-floor boreholes within the placement room could cause localized damage at the roof of the placement room, around the boreholes and in the rock web between two adjacent boreholes. In comparison with the elliptical-shaped room, the localised damage is more severe in the circular-shaped room. For the circular-shaped placement room, the thickness of the damage zone is estimated to be less than 0.125 m at the roof of the placement room, about 0.24 m near the borehole and decreases to 0.02 m at the mid-point of the rock web between two boreholes and less than 0.07 m around the boreholes. How far the failure zone will progress is unclear.

Based on coupled T-M far-field analyses, the peak temperatures at various regions in the repository were determined. The maximum thermally induced uplift at the ground surface above the centre of the repository would be about 0.2 m. The maximum subsidence induced by ice load on the ground surface would be about 6.4 m at 96,000 years.

ABSTRACT

Title: **Hydrogen Effects on Carbon Steel Used Fuel Containers**
Report No.: **NWMO TR-2009-29**
Author(s): Fraser King
Company: Integrity Corrosion Consulting Ltd
Date: December 2009

Abstract
Hydrogen affects the properties of many structural materials including steels and, more particularly, the general class of carbon steels from which a used fuel container would likely be fabricated. Degradation of the mechanical and corrosion properties of steels can take many forms but, in general, the severity of damage increases with increasing absorbed hydrogen concentration, increasing stress, and increasing strength of the material.

Various aspects of the possible hydrogen-related damage of used fuel containers (UFC) are reviewed, including (i) the generation and absorption of hydrogen due to aqueous corrosion and from the gaseous H_2 phase that will form in the repository, (ii) the diffusion of hydrogen through the container wall and the interaction of H with various kinds of trap sites, (iii) the resultant forms of damage and the mechanisms proposed to account for this damage, (iv) threshold conditions that can be used to predict the susceptibility of UFC in the repository environment, and (v) the implications for the containers, including an assessment of the most likely forms of H-related damage, a prediction of the susceptibility of the containers, an assessment of the period during which H-related damage is possible, and possible mitigation strategies based on the container material and design.

Of the various forms of H damage, those deemed most likely to affect the containers are blister formation or hydrogen-induced cracking and cracking associated with the inner surface of the closure weld once gaseous hydrogen has entered the void space inside the container. Overall, however, the probability of H-related failure is considered small because of the benign nature of the environment, the low applied and residual stresses, and the low strength of the container material.

This low probability of failure due to H damage can be reduced even further through proper selection of the container material and of the design of the closure weld.

Although the susceptibility to H-related damage is judged to be minimal for a UFC, the period of greatest susceptibility extends throughout the long-term anaerobic period in the evolution of the repository environment. Therefore, unlike other forms of localized damage such as stress corrosion cracking and localized corrosion which are only possible during the initial short aerobic transient period, H-related damage is possible for the vast majority of the container design life.

ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2009 Update**
Report No.: **NWMO TR-2009-30**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2009

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 updates the 2008 report [Garamszeghy, 2008] and summarizes the existing inventory of used CANDU nuclear fuel wastes in Canada as of June 30, 2009 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors.

As of June 30, 2009, a total of approximately 2.1 million used CANDU fuel bundles (42,000 tonnes of heavy metal (t-HM)) 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 about 2.8 to 5.5 million used CANDU fuel bundles (56,000 t-HM to 110,000 t-HM), depending upon decisions to refurbish current reactors. This total projection has not changed since the 2008 report. The lower number is based on an average of 30 calendar years of operation for each reactor (i.e. no refurbishment), while the higher number assumes that reactors are refurbished and life extended for an additional 30 calendar years of operation.

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 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 1.9 million CANDU fuel bundles (31,200 t-HM), or 21,600 PWR fuel assemblies (11,640 t-HM), or 27,000 BWR fuel assemblies (3,384 t-HM), or some combination thereof. This total has been reduced from the 2008 report due to cancellation of some new-build plans in Ontario.

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: **Coupled Thermal-Hydraulic-Mechanical Modelling of the Canister Retrieval Test**
Report No.: **NWMO TR-2009-31**
Author(s): R. Guo
Company: Atomic Energy of Canada Limited
Date: October 2009

Abstract
One of the in-situ tests chosen for examination as part of a series of numerical simulations undertaken as part of the Engineered Barriers Systems Task Force (EBS-TF) is the Canister Retrieval Test (CRT) carried out in the Äspö Hard Rock Laboratory. The Canister Retrieval Test basically aims at demonstrating the readiness for recovering emplaced containers after the bentonite is fully saturated and has developed its maximum swelling pressure. The test also studied the thermal, hydraulic and mechanical evolution in the buffer from start until full water saturation. In the CRT, an electrically heated full-scale container was lowered into a deposition hole lined with blocks and rings of bentonite clay in the fall of 2000 and retrieved early in 2006, after five years of operation. A large number of instruments measured pressure, temperature and other parameters during this time. In order to evaluate the effectiveness of the CODE_BRIGHT modelling code in predicting the evolution of the coupled processes in unsaturated clay material, the one-dimensional and two-dimensional coupled thermal-hydraulic (TH) and coupled thermal-hydraulic-mechanical (THM) simulations for the CRT were conducted using CODE_BRIGHT. The simulated results are compared with measurements and presented in this report.

ABSTRACT

Title: **Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology – Annual Report 2009**
Report No.: **NWMO TR-2009-32**
Author(s): David Jackson and Kenneth Dormuth
Company: David P. Jackson & Associates Ltd.
Date: December 2009

Abstract
This is the 2009 Annual Report of the NWMO watching brief on Reprocessing, Partitioning, and Transmutation (RP&T) and Alternative Waste Management Technologies.

In this report the situation following the virtual cancellation of the US Yucca Mountain project, which includes the potential for a US RP&T program, is discussed. In Europe, nuclear power has been recognized as a sustainable energy option and a comprehensive R&D plan has been developed including a commitment to closed fuel cycles.

The resurgence of interest in thorium fuels is briefly reviewed, but there has been little progress in developing the commercial scale RP&T necessary for the deployment of these fuels.

Recent work in estimating the costs of aqueous reprocessing of used LWR fuels is applied to assess the costs and feasibility of reprocessing of CANDU fuels with the conclusion that it would be prohibitively expensive and, based on recent experience in Japan, would require decades to implement. Volume reduction for CANDU used fuel would depend on the reprocessing system used but plausibility arguments indicate that it might be difficult to achieve.

Sandia Laboratories has produced a preliminary evaluation of very deep borehole disposal of used fuel from the U.S. reactors, indicating excellent long-term safety. The study also indicates that construction costs for very deep borehole disposal of light water reactor fuel would be competitive with a mined repository. However, we estimate that the cost of constructing very deep boreholes for disposal of existing CANDU fuel waste in Canada would be significantly greater than that for light water reactor fuel on a per-kilowatt-hour basis. Further work would be required to adequately compare the total life-cycle costs for very deep borehole disposal of Canada's used fuel with the current concept of Adaptive Phased Management. As well, use of the very deep borehole design described in the Sandia study would virtually eliminate the possibility of demonstrated long-term retrievability, a key feature in Adaptive Phased Management.

ABSTRACT

Title: **ORIGEN-S Decay Heat Calculations from NuFLASH and SORO Detailed Bundle Data**
Report No.: **NWMO TR-2009-33**
Author(s): Mike Seager, Andy Inglot
Company: AMEC-NSS
Date: December 2009

Abstract
As part of the Nuclear Waste Management Organization's (NWMO) program to investigate the integrity of used nuclear fuel, the temperature of an instrumented Dry Storage Container (DSC) DSC-812, loaded with 384 CANDU fuel bundles, was monitored at the Western Waste Management Facility (WWMF) starting in September 2007. The NWMO requires key data including used fuel burn-up and heat of decay (thermal output) for each of the fuel bundles stored in the DSC including their location within the storage modules and the DSC. This information will form part of a planned subsequent study to complete a thermal analysis of DSC-812.

The decay heat for 22 representative bundles out of 384 bundles in DSC-812 was calculated with ORIGEN-S using bundle data extracted from the NuFLASH fuel accounting database and the SORO production physics database. It was also found that the ORIGEN-S predicted decay heat for a representative bundle is independent of the bundle power history. Finally, the upper-bound 1-sigma uncertainty in the predicted decay heat calculations at decay times between 10 and 15 years is estimated to be 10%. The report provides the methodology, key calculations, and results.

ABSTRACT

Title: **Hydraulic-Mechanical (H-M) Numerical Modelling of Triaxial Tests of Unsaturated Clay-Based Sealing Material Using Three Computer Codes**
Report No.: **NWMO TR-2009-34**
Author(s): D.G. Priyanto and D.A. Dixon
Company: Atomic Energy of Canada Limited
Date: December 2009

Abstract
This document discusses numerical modelling of the hydraulic-mechanical (H-M) behaviour of unsaturated clay-based sealing material. The discussion includes: calibration of the constitutive model parameters from laboratory test results, modification of the existing constitutive model, and application of this constitutive model in three computer codes.

The triaxial test results for compacted bentonite-sand buffer (BSB) material in unsaturated conditions are used to calibrate the H-M constitutive model parameters. The BSB is a 50:50 mixture (by dry mass) of bentonite and well-graded silica sand compacted at high dry density of approximately 1.67 Mg/m^3. The parameters of the existing constitutive models for the BSB have been calibrated using laboratory test results, including van Genuchten (1980) model to simulate the hydraulic behaviour and Basic Barcelona Model (BBM) (Alonso et al. 1990) to simulate mechanical behaviour.

Modifications of these two existing constitutive models are introduced. First, a new mechanical constitutive model (called the BSB model) is introduced. This model removes the coupling of the yield line and coefficient of the compressibility in the BBM and makes the parameter calibration easier. Second, a new hydraulic constitutive model, porosity-dependent soil water characteristic curve (SWCC), is introduced. This model is able to replicate the results of laboratory tests, where maximum gravimetric water content (w) is linearly dependent on the total porosity.

Finally, three computer codes based on the finite element methods (i.e., CODE_BRIGHT and COMSOL) and finite difference methods (i.e., FLAC) have been used to simulate the H-M behaviour of the BSB in triaxial infiltration tests. The results of simulations are presented and discussed.

ABSTRACT

Title: **Field measurements of the transfer factors for iodine and other trace elements**
Report No.: **NWMO TR-2009-35**
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Abstract
Iodine-129 is one of the key radionuclides related to environmental assessments of nuclear fuel waste management because it has a very long half-life, is environmentally mobile, and iodine (I) is an essential element for animals. However, data are sparse because both ^{129}I and stable I are difficult to detect. In this study, a new method has been adopted that allows reliable measurement of stable I in almost all biological tissues. This method was used to survey transfer factors from media (water and soil) to a variety of Canadian plants and animals. In addition to iodine, up to 62 other elements were measured.

The plants and animals considered are relevant to the human food chain. The data include both traditional farm products, as well as a variety of wild fish and game. The food products related to modern agriculture included a comparison of garden versus field crops, as well as transfers to milk, eggs and meat. The survey of meat products included beef, pig and chicken and was augmented by single samples of rabbit, lamb, squab (domestic pigeon), turkey and domestic goose. The wild animal data is relevant to both a hunter lifestyle, as well as providing information on movement of iodine and trace elements through biota of general interest. The data included 9 species of wild fish as well as wild deer, geese and blueberries. Additional single samples of caribou, elk and moose extended the range of species. The resulting transfer factors were fish/water concentration ratios, meat/feed concentration ratios and feed-to-meat fractional transfer factors. Soil and sediment solid/liquid partition coefficients, a survey of iodine concentrations in 20 lakes and aquatic macrophyte/water concentration ratios were also completed.

In general, where comparisons to the literature were possible, there was good agreement. However, this study markedly increased the number of data for iodine over what was previously available, and coupled these with data from the same systems for many other elements of interest. There was strong evidence that meat transfer factors might be more consistently expressed as concentration ratios rather then the traditional fractional transfer factors.