

Technical Research and Development Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2007

NWMO TR-2008-01

March 2008

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Nuclear Waste Management Organization

nwmo

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ABSTRACT

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

Abstract

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

Significant achievements in 2007 include:

- Co-operation agreements were signed with Posiva (Finland), SKB (Sweden), Nagra (Switzerland) and Andra (France). These agreements will facilitate the exchange of information and participation in joint research projects.
- Canada participated in several projects at the SKB Äspö Hard Rock Laboratory in Sweden, including the Colloid Dipole Experiment, the LASGIT Gas Injection Test, the Engineered Barrier System Modelling Task Force, the Groundwater Modelling Task Force, the Long-term Test and Canister Retrieval Tests, the ROSE (rock-shear) test design, and the BACLO (backfill) project. NWMO also hosted the Äspö Modelling Task Force 7A Meeting #23 in Toronto.
- An annual technical research and development program update was held with the Canadian Nuclear Safety Commission.
- A Workshop on Used-Fuel Container Corrosion was held to discuss the current state of knowledge on corrosion of copper and steel used-fuel containers in both crystalline rock and sedimentary rock repository environments.
- A conceptual model for corrosion of a carbon steel used fuel container in a deep geological repository in sedimentary rock was developed to account for various corrosion processes that might affect the container in the repository environment.
- The potential impacts of microbial activity and salinity on the design of repository sealing system components were studied, with an emphasis on the bentonite buffer which would surround the used-fuel containers. The experimental results suggest that in a low-salinity repository environment, a bentonite dry density of 1.6 g/cm³ and the associated high swelling pressure would be required to suppress microbial activity in bentonite.
- The 5th Annual NWMO Geoscience Seminar was held to discuss the state-of-knowledge in site characterization tools and methods, geoscientific experiments, performance assessment, flow system evolution and geosphere stability.
- The development of laboratory technique and protocols for the characterization of sedimentary rocks continued with investigating the feasibility of the ultracentrifugation method for pore water extraction and comparing the standard through-diffusion and an x-ray radiography technique for the determination of diffusive properties of rocks.

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

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1. INTRODUCTION

In January 2007, the Nuclear Waste Management Organization (NWMO) assumed responsibility for directing and managing all aspects of the established technical research and development (R&D) program for Canada's used nuclear fuel. The technical R&D was previously directed and managed by Ontario Power Generation (OPG) from 1996 to 2006.

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

Adaptive Phased Management (APM) has the following characteristics:

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

A summary of progress in 2007 for the NWMO's technical R&D program for long-term management of Canada's used nuclear fuel is described in this Annual Technical Report.

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 REGULATORY FRAMEWORK

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

In 2004, the CNSC published Regulatory Policy P-290, *Managing Radioactive Waste*. This Regulatory Policy P-290 states the following principles:

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

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

With respect to a deep geological repository for used nuclear fuel, the need for a CNSC licence triggers application of the *Canadian Environmental Assessment Act* (CEAA). Under the CEAA, an environmental assessment is required to assess the environmental effects of most projects requiring federal action or decisions.

The regulatory framework includes specific opportunities for public input at appropriate stages in the licensing process.

2.2 TECHNICAL PROGRAM OBJECTIVES

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

- i. Maintain skilled technical capability by developing in-house expertise and effective working relationships with Canadian universities and the consulting community.
- ii. Enhance scientific understanding of the technology for central storage and long-term containment and isolation of used fuel in a deep geological repository.
- iii. Further develop capability to evaluate potential sites from a technical perspective.

- iv. Seek opportunities for international collaboration and participation in joint technical research, and development and demonstration programs, to bring the best international knowledge and practices into the technical work of the NWMO.
- v. Build understanding of monitoring and retrievability during the various stages of implementation.
- vi. Maintain awareness of alternative means for the long-term management of used nuclear fuel.
- vii. Revise and update the cost estimate for long-term management of Canada's used nuclear fuel.
- viii. Incorporate Aboriginal Traditional Knowledge into technical research and development.

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

A list of the technical reports produced in 2007 is provided in Appendix A.1 and A.2. All technical reports published before 2000 are listed in Garisto (2000), while the 2000 to 2006 reports are listed in corresponding annual progress reports (Gierszewski et al. 2001, 2002, 2003, 2004a; Hobbs et al. 2005, 2006; Russell et al. 2007).

Appendix A.3 summarises the papers and presentations made in 2007 by technical program staff and contractors.

Appendix A.4 provides a list of PhD theses prepared for the technical work program.

Appendix A.5 provides a list of the primary external contractors and collaborators for the technical work program.

Abstracts of all reports produced by this program in 2007 are included in the final part of this Annual Technical Report (Appendix B).

2.3 INTERNATIONAL ACTIVITIES

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

Since 2004, Canada has been participating in experiments at the SKB Äspö Hard Rock Laboratory (HRL). The purpose of this participation is to improve our understanding of key

processes in a repository through working on large-scale projects, and to directly share lessons learned in repository technology development and site characterisation.

In 2007, NWMO and its expert consultants participated in the Colloid Dipole Experiment, the LASGIT Gas Injection Test, and the Engineered Barrier System Modelling Task Force and Groundwater Modelling Task Force groups. Support was also provided with respect to the Long-term Test and Canister Retrieval Tests, the ROSE (rock-shear) test design, and the BACLO (backfill) project.

NWMO continues to participate in the international radioactive waste management program of the OECD Nuclear Energy Agency (NEA). Members of this group include all the major nuclear energy countries, both waste owners and regulators. This group co-ordinates several activities. In 2007, Canada actively participated in the NEA *Thermodynamic Database Project*, the *Safety Case Symposium* and the *AMIGO Project*.

NWMO also supported the International DECOVALEX III Project (research on the application of coupled thermo-hydraulic-mechanical numerical models in the geosphere) and BIOPROTA (international working group on biosphere modelling).

3. REPOSITORY ENGINEERING

The main objectives of the repository engineering program are to develop engineering data, models, methods and tools necessary for assessing the safety of the deep geological repository concept and for future siting investigations; to develop reference and alternative conceptual designs for the components of a used fuel repository system to support the feasibility of the concept; and to support the development of cost estimates for long-term management of Canada's used nuclear fuel.

In the following sections, the status of the repository engineering program and the achievements in 2007 are outlined for work activities related to the development of used fuel integrity, container corrosion, repository sealing material development and repository design.

3.1 USED FUEL INTEGRITY

Used nuclear fuel may be in storage for many decades before it is placed in a deep geological repository. Therefore, it is essential that the fuel maintains its integrity at all times.

While in the reactor, a CANDU fuel bundle is subjected to a number of processes which may affect its material properties. For example, irradiation effects and thermal and mechanical stresses can lead to changes in fuel bundle material properties, built-in stresses and bundle deformations. Post in-reactor handling of the fuel bundles may also contribute to additional loadings that could have an impact on fuel bundle integrity.

Currently, the rate of defected fuel in the CANDU fuel population is very small (on the order of 0.01%) based on post-irradiation examinations (PIE). Observations from PIE are intended to provide the status of the integrity of the fuel as well as discover any changes in the reactor operations that could impact the fuel's structural integrity. The general conclusion from PIE is that the condition of used CANDU fuel meets expected performance requirements and the fuel is structurally sound.

A standard CANDU fuel bundle is shown in Figure 3.1.



Figure 3.1: CANDU fuel bundle – 20 kg uranium, 0.5 metre length

3.1.1 Development of CANDU Bundle Stress Model

Following an assessment of potential processes that could lead to the loss of fuel bundle integrity in dry storage over time, delayed hydride cracking was identified as an area of potential concern. In particular, the endcap/endplate welds were identified as an area of interest since delayed hydride cracking of the endcap/endplate welds could occur as a result of the presence of hydrogen or deuterium in the endcap/endplate weld region if sufficient stresses are present in this location of a CANDU fuel bundle.

To determine the stresses in a CANDU fuel bundle and at the endcap/endplate weld, modelling the bundle response to applied loads may be used to understand its mechanical behaviour and for predicting its long-term integrity in dry storage.

On behalf of the NWMO, Nuclear Safety Solutions Ltd. is developing a finite-element model (FEM) to describe the stresses in 28-element and 37-element CANDU fuel bundles using the code ANSYS. The models were tested for a range of possible stresses. Model verification was conducted using laboratory tests with non-irradiated fuel bundles at Stern Labs by pulling on the top outer fuel element while the bundle was restrained at the endplates. The element and bundle displacements were measured at several locations and at the endplates. A similar push test on the top outer elements of the bundle was done with similar measurements as per the pull test.

Typical displacement data for the pull-test are shown in Figure 3.2 for the mid-point of the pulled element compared against the results of the simulation. The results show a general good agreement with the FEM at the linear elastic range relevant to dry storage conditions, but experiment and simulation results diverge as the bundle loading moves progressively into the plastic region. Further divergence was shown next to the endplates.

When the push-tests are compared with the model predictions of displacement, the agreement between the experimental results and the model begins to diverge, although the results from the model are trending in the right direction as indicated in Figure 3.3. Greater divergence in the comparison was found in the displacement at the endplate. It was also found that the displacements at both ends of the bundle showed some asymmetry which may be due to variance of material properties at the endcap/endplate welds and the overall behaviour of the bundle array acting as a complex "spring".

Further work on developing and documenting the bundle stress model and analyses are planned for 2008 to examine the potential effects of the variance of material properties at the endcap/endplate welds and to improve our understanding of CANDU fuel bundle behaviour in dry storage.

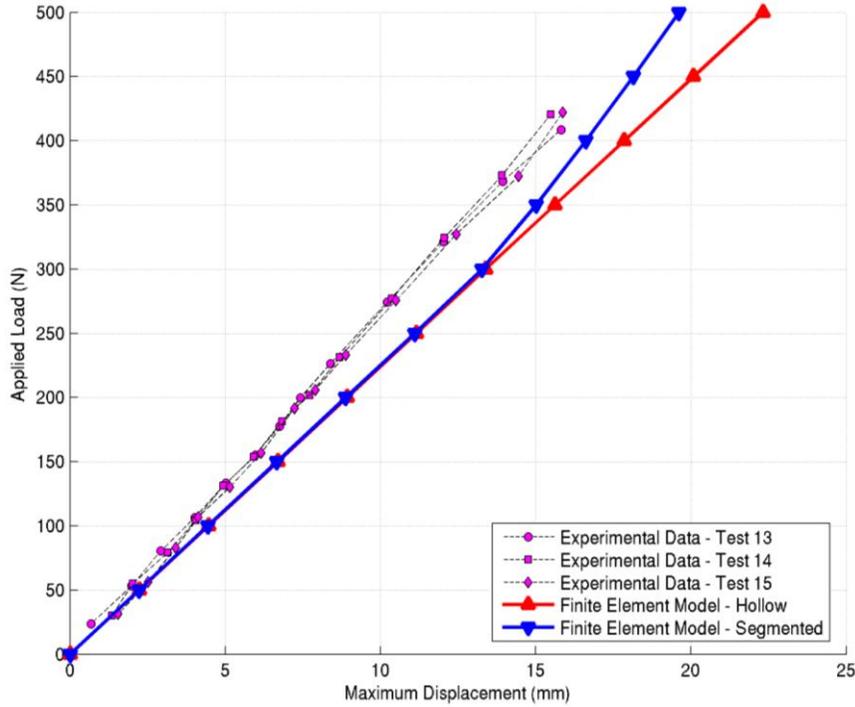


Figure 3.2: Load LVDT displacement for 28-element pull test

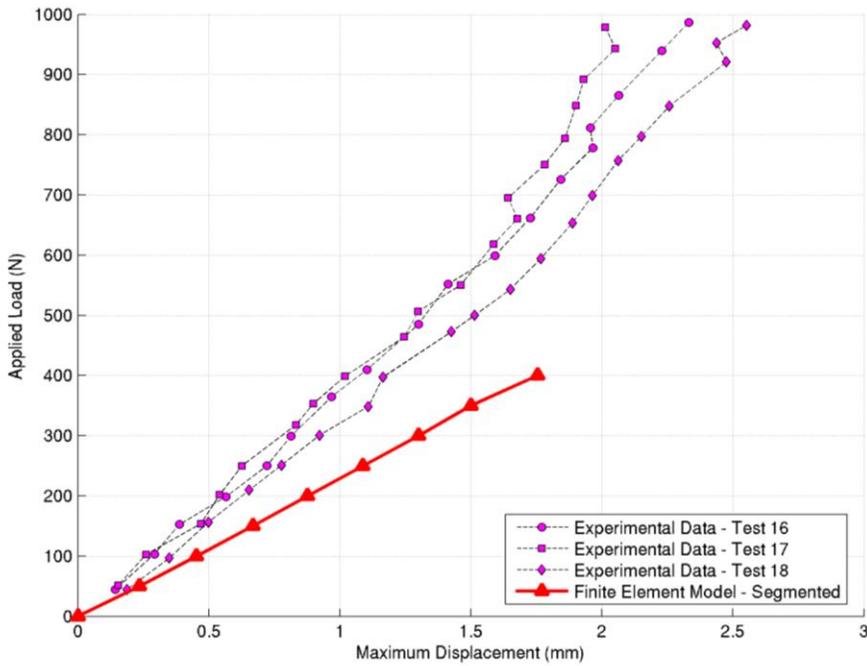


Figure 3.3: Load LVDT displacement for 28-element push test

3.1.2 Delayed Hydride Cracking (DHC) Test Methodology and Test Apparatus

Delayed hydride cracking (DHC) of the endcap/endplate welds is considered to be an important mechanism that could potentially affect the bundle integrity during dry storage. To further gather information on the properties of the bundle endcap/endplate welds and to determine whether DHC could be a concern, an apparatus and methodology was developed that could be implemented in a hot-cell to test endcap/endplate welds of irradiated fuel. Parameters of interest include the stress intensity factor that can lead to endcap/endplate crack formation and a determination of the crack velocity of endcap/endplate welds of irradiated fuel as a function of temperature from as low as -50°C to as high as 150°C .

In 2007, the first phase of the experimental program was completed by developing an apparatus and testing the methodology on non-irradiated endcap/endplate welds from a CANDU fuel bundle. The methodology is based on a bending test by applying a torque on the endcap/endplate weld. The loading supplied by the torque is measured and the growth of the crack is followed by measuring the potential drop along the crack and by acoustic emission. A photograph of the DHC test apparatus is shown in Figure 3.4.

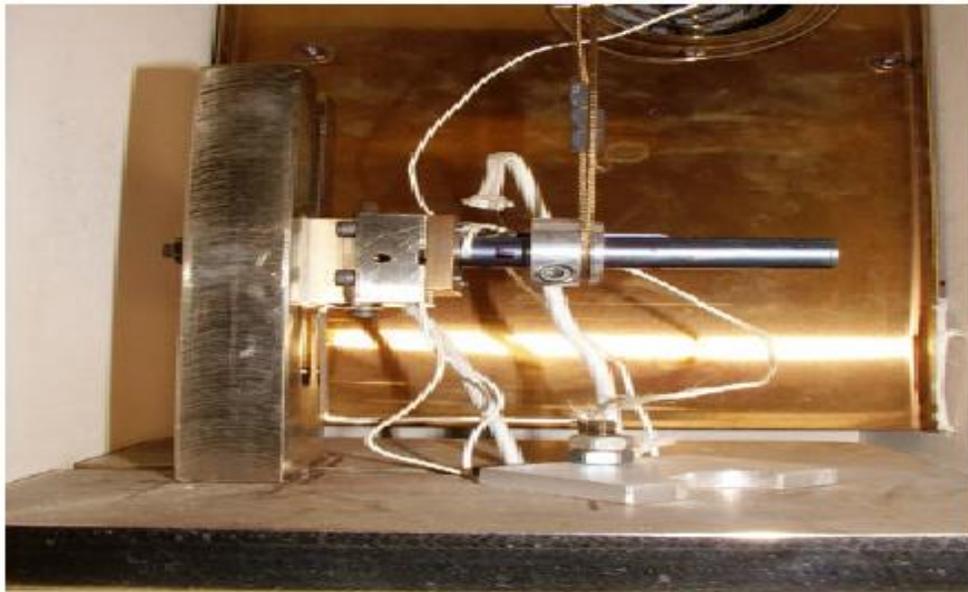


Figure 3.4: Photograph showing the sample in the DHC Test apparatus

Results of the tests indicated that the test apparatus was successful in initiating and following crack growth of the endcap/endplate weld. A typical crack is shown in Figure 3.5. The crack begins at the notch of the endcap/endplate weld, before proceeding into the weld material in the direction of the endplate as loading from the bending stress is increased. The weld notch acts as a stressor from where the crack grows.

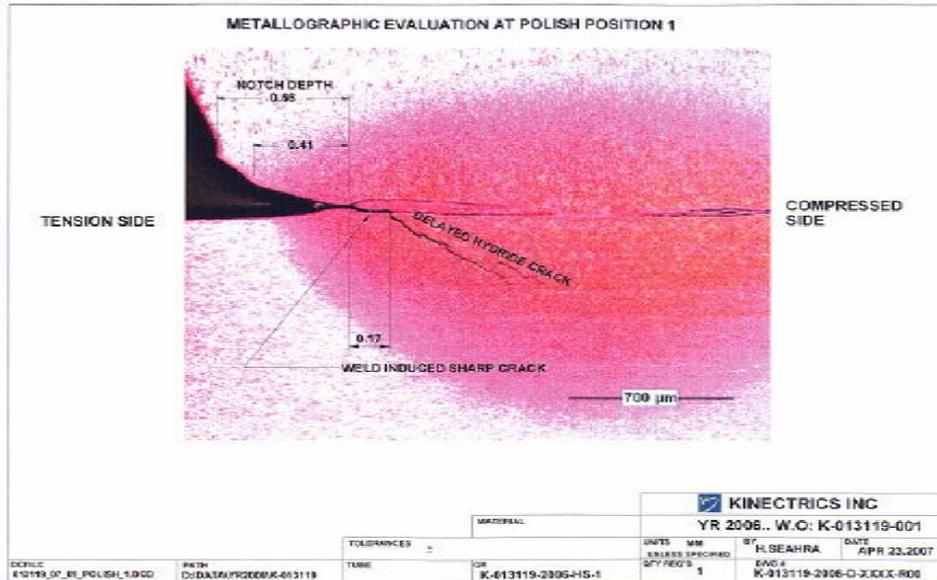


Figure 3.5: Metallographic section of sample from Test 07-09 showing the weld notch, weld discontinuity and DHC crack

The test material from the fuel bundle had a hydrogen concentration in the Zircaloy matrix of about 10 ppm. This material was used to confirm whether DHC could be operative at concentrations of hydrogen which are nominal for a manufacturing bundle and to scope a series of tests with endcap/endplate welds with concentrations relevant to those found in irradiated CANDU fuel. The results confirmed that DHC could be operative at this small concentration for a stress intensity factor of about $13 \text{ MPa m}^{1/2}$.

In preparation for testing irradiated endcap/endplate welds, a series of tests were done at various temperatures and loadings to further develop the methodology and provide benchmarking results for the irradiated tests. For this series of tests, the bundle cladding and endcap/endplate welds were loaded electrochemically with hydrogen to a level of about 40 ppm. The tests results were assessed with both analytical stress intensity factor equations relevant to the geometry of the test samples and with a finite element code developed for the purpose. The finite element code calculated stress intensity factors which are in agreement with the analytical models. Delayed hydride cracking was confirmed through analysis of the crack morphology through Scanning Electron Microscopy (SEM). Stress intensity factors (K_{IH}) from the tests are about $8\text{-}14 \text{ MPa m}^{1/2}$ and crack velocities of the order of 10^{-9} m/s .

A report on DHC test methodology and test apparatus is planned for 2008.

3.1.3 Temperature Monitoring of a Dry Storage Container (DSC)

An OPG Dry Storage Container (DSC-812) was manufactured and instrumented with thermocouples to obtain a temperature record of a DSC after loading with used CANDU fuel in order to conduct a detailed thermal analysis of a DSC at OPG's Western Waste Management Facility. An illustration of a DSC for used CANDU fuel is shown in Figure 3.6.

Thirty-two thermocouples were installed in the concrete wall of the DSC next to the inner and outer steel liners as well as in the DSC lid. Monitoring of the temperatures was done by collecting data from the thermocouples in a datalogger, and retrieving and analysing these data at regular intervals over a three month period in the fall of 2007.

Thermal analysis of DSC-812 is planned for 2008.

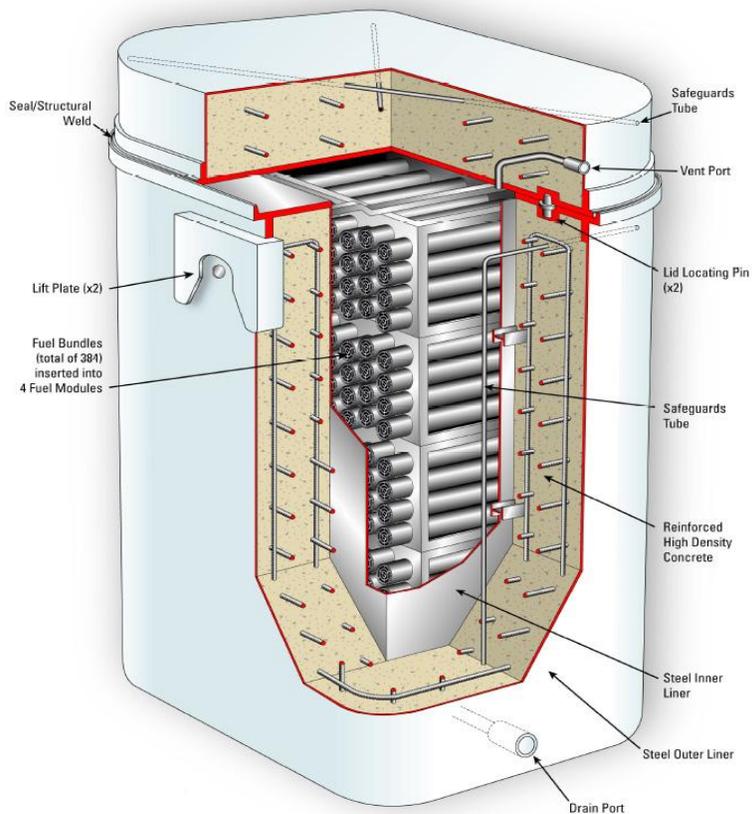


Figure 3.6: Dry Storage Container (DSC) for used CANDU fuel

3.2 CONTAINER CORROSION

3.2.1 Container Corrosion Workshop

A two-day NMWO-sponsored Workshop on Used-Fuel Container Corrosion was held in Toronto on June 12 and 13, 2007. An illustration of the design for the copper used fuel container is shown in Figure 3.7. The workshop was attended by a number of corrosion researchers and experts from the industry and universities. The current state of knowledge and gaps on corrosion of copper and steel used-fuel containers in both crystalline rock and sedimentary rock repository environments were discussed based on the Canadian technical R&D program and other international radioactive waste management programs. The findings are summarized in a container corrosion overview report (King 2007a).

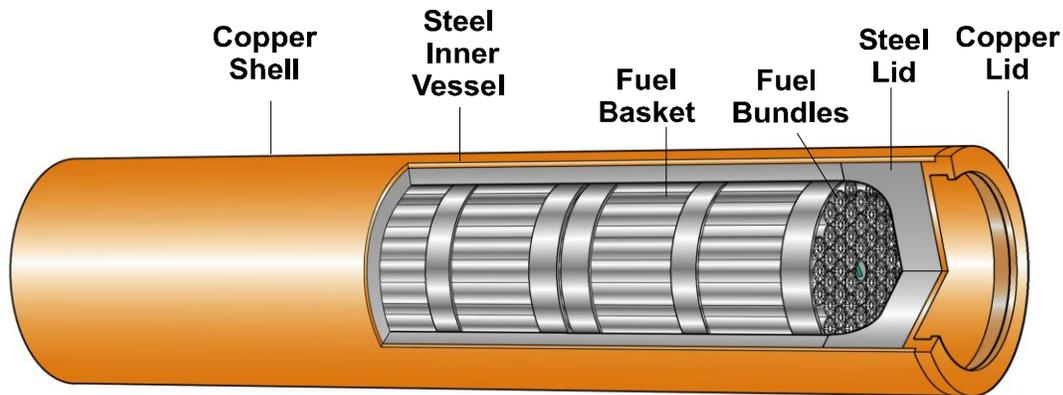


Figure 3.7: Copper used fuel container

3.2.2 Corrosion Model

A conceptual model for corrosion of a carbon steel used-fuel container in a deep geological repository in sedimentary rock was developed in 2007 (King 2007b). The model takes into account various corrosion processes that might affect the container in the repository environment which include uniform corrosion, localized (pitting) attack, hydrogen-related effects, stress corrosion cracking, microbologically influenced corrosion, preferential weld corrosion, and dry air oxidation. This analysis suggests that carbon steel containers can provide containment of used fuel for substantial periods of time in a deep geological repository in sedimentary rock.

3.2.3 Copper Corrosion Experiments

Stress corrosion cracking (SCC) of copper containers in a deep geological repository may be possible in the presence of sufficient stresses, oxidant and corrosion agents such as ammonia, acetate and nitrite. The presence of chloride ion in a deep geological repository will suppress

the SCC susceptibility. Most the SCC experiments have been performed to date at room temperature and there is a need to assess the effect of elevated temperatures on the SCC behaviour. SCC tests were carried out on oxygen-free phosphorous-doped copper specimens in nitrite-only solutions and in various nitrite/chloride mixtures at elevated temperatures of 100°C and 130°C (Ikeda and Litke 2007). The results were compared with the results of previous SCC tests at room temperature of 22°C. The present results show that SCC in nitrite and nitrite/chloride environments is suppressed at elevated testing temperatures. It is concluded that the 100°C SCC behaviour of copper in these environments can be conservatively assessed from SCC tests at room temperatures.

3.3 SEALING MATERIAL DEVELOPMENT

The NWMO has continued to develop sealing material concepts through the use of laboratory testing and numerical modeling. In 2007, the laboratory testing program included a long-term study to assess the sealing capabilities of various bentonite materials and microbial studies of bentonite sealing materials and Opalinus Clay. The numerical modeling studies include a study of the swelling and non-swelling clay for the in-floor borehole method and a thermohydraulic (T-H-M) analysis of unsaturated buffer and host rock.

In an on-going, long-term laboratory testing program, sealing materials were placed in cells with an unrestricted fluid supply simulating anticipated conditions in a deep geological repository. In 2007, two of the tests were dismantled and no evidence of seepage through the upper 50 mm barrier was evident after a period of 1.5 years, and no preferential pathways along the sealing material/liner interface were noted. An illustration of the laboratory testing apparatus is shown in Figure 3.8.

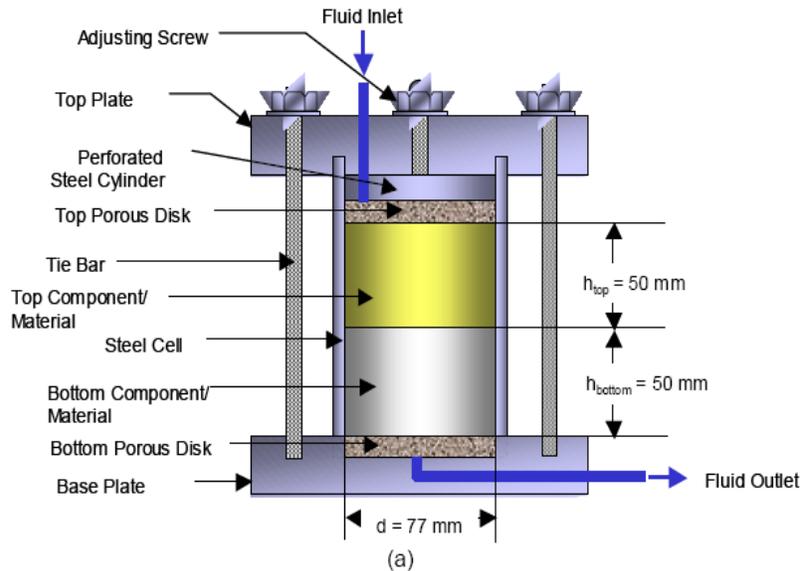


Figure 3.8: Illustration of laboratory-scale sealing material tests

A numerical analysis of the swelling and non-swelling clay materials upon full saturation was carried out for the in-floor borehole placement method geometry using the Fast Lagrangian Analysis of Continua (FLAC) analysis software. The modelling results suggest that the density of compacted bentonite, as well as the density of pre-compacted bentonite pellets, remain relatively high in the annular region between the container and the borehole. The predicted density remains high in spite of the bentonite backfill expanding out of the borehole about 4 cm into the placement room above. The model simulation suggests that container will move upwards as the dense bentonite backfill swells, but that this movement would be less than 1 cm.

3.3.1 Microbial Studies in Repository Sealing Systems and Opalinus Clay Samples

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

In a low-salinity repository environment, at or less than 50g/L, the experimental results indicate that high bentonite dry density ($\geq 1.6 \text{ g/cm}^3$) and the associated high bentonite swelling pressure would be required to suppress the microbial activity (Stroes-Gascoyne et al. 2007).

In a high salinity repository environment, at or in excess of 100g/L, the experimental results indicate that salinity is the dominant factor for controlling the microbial activity. In this case, microbial activity can be suppressed at low bentonite density (i.e., dry density as low as 1.0 g/cm^3). These results suggest that in low-salinity repository environments, the container placement method and design of the repository sealing system would need to ensure that the bentonite density will remain high during the transition period to full saturation and at times when all sealing system components are equilibrated. In high-salinity repository environments, the ability to achieve high bentonite density to suppress microbial activity would have a smaller impact on the container placement method and design of the repository sealing system.

Further microbial studies are being initiated to assess the microbe-inhibiting performance of compacted bentonite at salinities between 50 and 100 g/L.

Samples of the Opalinus Clay from the Cement Interaction (CI) Experiment and the Porewater Chemistry (PC) Experiment at the Mont Terri Underground Research Laboratory in Switzerland were examined at AECL's Whiteshell Laboratory for viable and culturable microbiological populations. The initial findings indicate that undisturbed Opalinus Clay appears to contain very small culturable populations of anaerobic microorganisms, but the viable population derived from phospholipid fatty acid analysis appears to be several orders of magnitude larger. The introduction of synthetic porewater in the Porewater Chemistry borehole contained large culturable populations of both aerobic and anaerobic microorganisms, including sulphate-reducing bacteria (SRB) after an undisturbed equilibration period of three years with the formation water.

The significance of introducing microorganisms into the Opalinus Clay formation will require further study and analysis to assess the potential impact on engineered barriers systems in a repository.

3.3.2 Participation in Engineering Barrier Task Force

NWMO is continuing to participate in the Engineering Barrier Task Force (EBS TF) modelling group via numerical modelling expertise at AECL. In 2007, two large in-situ experiments previously conducted by AECL at their Underground Research Laboratory, the Buffer Container/Experiment (BCE) and the Isothermal Test (ITT), were used as case studies by the international modelling group. Guo (2007a) modelled these experiments according to the EBS TF specifications and provided comparisons of the results with measured data to obtain a better understanding of the thermal, hydraulic and mechanical evolution in the buffer and the surrounding rock and interactions between the unsaturated buffer and the host rock.

Details of these underground experiments and the measured data obtained during the 6.5 years of water uptake for the ITT and the 32 months of water uptake including 29 months of heating of the BCE were previously described by Dixon et al. 2001.

The results from modeling these experiments using CODE_BRIGTH matched the measured data relatively well, which suggests a reasonable choice of thermal parameters for all the materials (Guo 2007a). The simulation of thermally induced moisture movement in the buffer in the buffer/container experiment captured the main characteristics of the moisture movement. Comparisons of the simulated pore water pressure in the rock with the measured data implies that the saturated permeability of the rock in the buffer/contact experiment ranged from $5 \times 10^{-20} \text{ m}^2$ for the ambient temperature rock to $5 \times 10^{-22} \text{ m}^2$ for elevated temperature rock. The results of the modeling imply that the permeability of the rock may be a function of temperature and stress. The numerical simulation was also found to capture the characteristics of the main mechanical behaviour of the buffer.

3.4 REPOSITORY DESIGN

Repository design initiatives in 2007 consisted of reviews of the existing technical literature, support of SKB's Rock Shear Experiment (ROSE) and numerical modeling of a deep geological repository using the in-floor borehole placement method.

In Canada, a significant research effort has been carried out over the past several decades to evaluate the potential suitability of crystalline rock as a host rock formation for a deep geological repository for used nuclear fuel. The NWMO's technical R&D program is also investigating the potential suitability of sedimentary rock as a host rock formation.

In 2007, NWMO conducted a preliminary evaluation of a number of repository engineering designs and placement methods for used fuel containers to help guide further development of generic repository designs and associated technologies for crystalline rock and for sedimentary rock in Canada. These repository designs and container placement methods included several variations of the in-floor borehole, in-room and horizontal borehole concepts developed in Canada and in other national radioactive waste management programs (e.g., Sweden, Finland, Switzerland, France, Belgium and Japan). An example of generic designs for a deep geological repository is given in Figure 3.9.

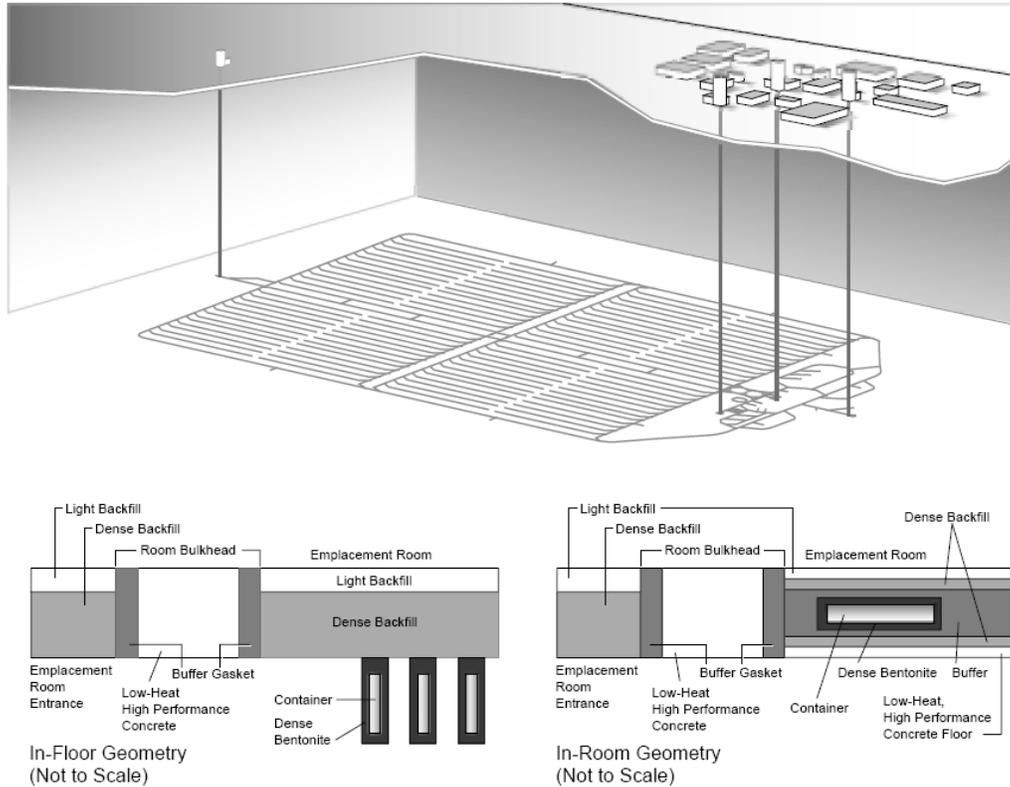


Figure 3.9: Deep geological repository – generic used fuel container placement designs for vertical in-floor borehole and horizontal in-room

The results of the preliminary evaluation suggested that the NWMO should continue to study and investigate several repository designs and container placement methods, given the generic nature of the used fuel research program in Canada. (The NWMO is now beginning to collaboratively develop a process for selecting a site with interested Canadians over the next few years (NWMO 2008)). These preferred repository designs and container placement methods include the in-floor borehole method for crystalline rock (e.g., RWE NUKEM 2003; SKB 2007), the in-room method for hard (i.e., lower rock creep rate) sedimentary rock (e.g., Nagra 2002), and the horizontal borehole method for soft (i.e., higher rock creep rate) sedimentary rock (e.g., Andra 2005).

NWMO recognizes that additional studies, analyses and site-specific information will be required before a reference design and used fuel container placement method can be developed for a deep geological repository for used nuclear fuel in Canada.

3.4.1 Technical Support to SKB's Rock Shear Experiment (ROSE)

The Rock Shear Experiment (ROSE) is a full-scale in-situ test proposed by SKB to investigate effect of earth-quake-induced rock shear on copper used fuel containers in a vertical borehole in granite at the Äspö Hard Rock Laboratory in Sweden. Small-scale laboratory testing is required to establish relevant design parameters for the ROSE.

In 2007, NWMO sponsored a Canadian consultant in rock mechanics from RSRead Consulting Inc. to join SKB staff for a review of laboratory equipment at the Tokai Research Centre of Japan Atomic Energy Agency (JAEA).

Based on observations of JAEA's test facility and meetings with JAEA staff, NWMO provided input to SKB's proposed testing and implementation plan.

3.4.2 Numerical Modelling of a DGR Using In-floor Borehole Placement Method

A series of three-dimensional finite element, thermal transient and thermal-mechanical stress analyses were performed to gain a better understanding of the behaviour of the plutonic rock mass in the near-field and far-field of a deep geological repository using an in-floor borehole placement method (Guo 2007b). The results of the modeling using CODE_BRIGHT match reasonably well with the results of a previous modeling assessment (RWE NUKEM 2003) program using ABAQUS for both the near-field and the far-field.

A coupled thermal-mechanical far-field three-dimensional model using the dimensions (horizontal dimensions for one quarter of a deep geological repository are 695 m x 725 m) for an in-floor borehole placement method was established, and based on this modeling, the following observations were made:

- From the near-field results, the peak container surface temperature at the centre of the repository is 89°C at 26 years after waste placement. This peak temperature calculated using CODE_BRIGHT is consistent with the previous peak temperature calculated using ABAQUS.
- From the far-field analyses, given an initial temperature of 17°C for a deep geological repository at 1,000 m depth, the calculated peak average temperature is 62°C at the centre of a repository, 41°C at the centre of an edge, and 30°C at the corner of a repository (see Figure 3.10). The time to reach the peak average temperature is 4,200 years after waste placement.
- From the far-field analyses, the maximum thermally induced uplift at the ground surface above the centre of the repository is 0.2 m. The time to reach the peak uplift is 8,000 years after waste placement (see Figure 3.11).
- From a comparison of the near-field and far-field analyses, the temperature results of the near-field analyses are valid for the first 800 to 1,000 years of repository heating after which the far-field analyses temperature results should be used.

The thermal-mechanical analysis of the in-floor placement method for used fuel containers in crystalline rock indicates that acceptable repository layouts can be achieved in a deep geological repository.

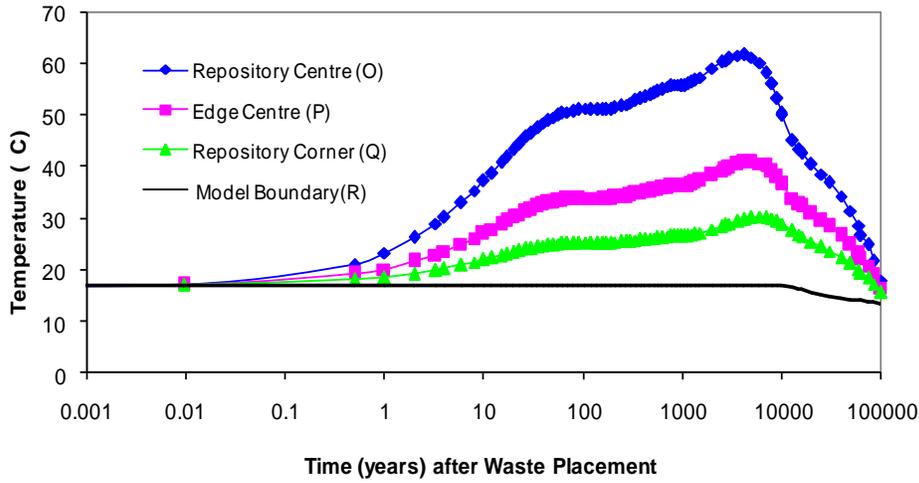


Figure 3.10: Far-field analyses temperature histories at four different locations

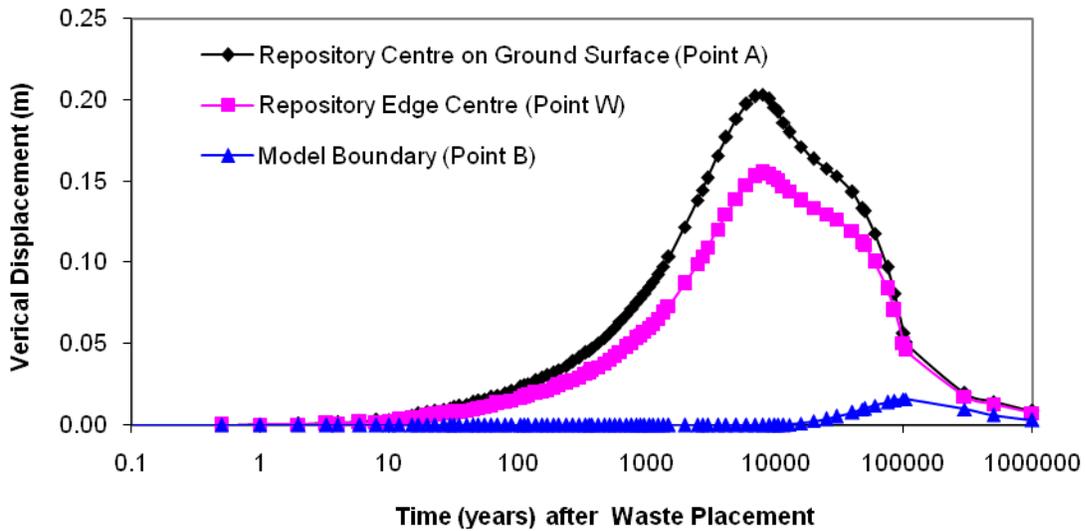


Figure 3.11: Thermally induced vertical displacements with time at three different locations on the ground surface (positive is upward)

4. GEOSCIENCE

4.1 INTRODUCTION

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

The main objectives of the geoscience work program are to:

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

The approach of the geoscience program is to integrate various work programs into illustrative case studies where multiple lines of evidence and reasoning are used to gain insight in the processes and mechanisms affecting the long-term geosphere stability and support the safety case for deep geological repositories.

The following sections outline the activities of the work program in 2007. The activities are organized into sections entitled developments of site characterization tools and methods, long term geosphere stability, numerical tools and methodologies and international projects.

4.2 DEVELOPMENTS OF SITE CHARACTERIZATION TOOLS AND METHODS

4.2.1 Canadian Shield Review – State of Geoscientific Knowledge

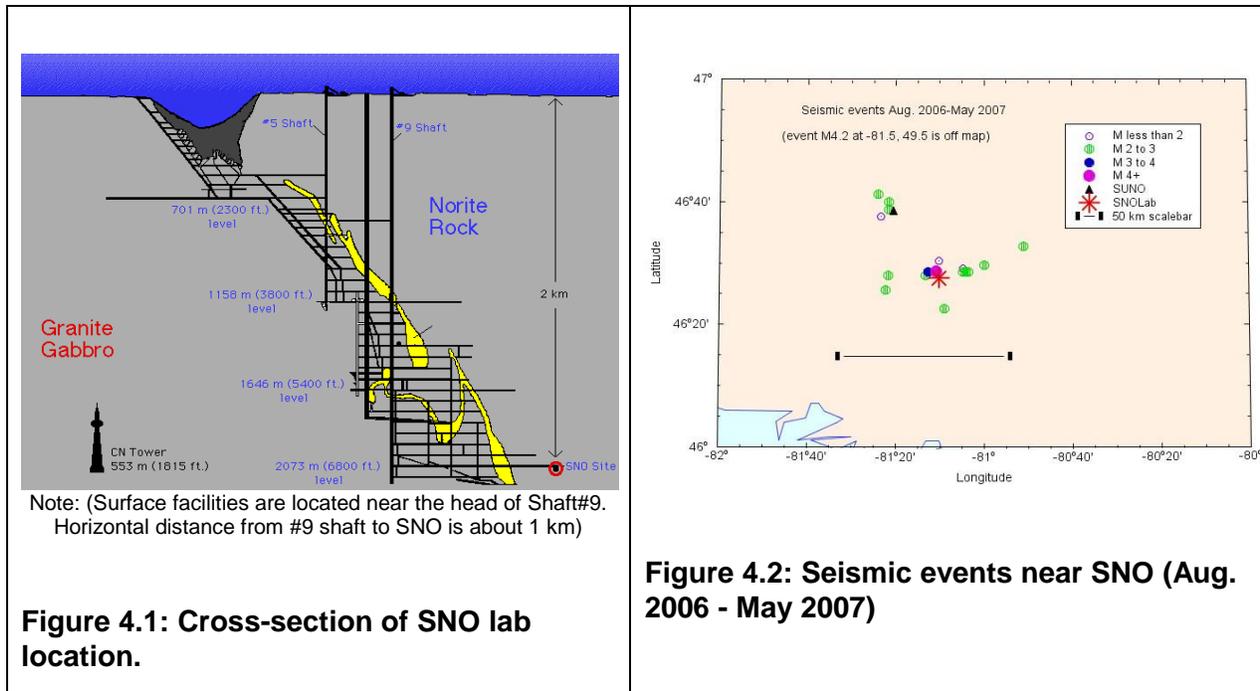
An updated report was completed in 2007, regarding the recent advances in the geology of the Canadian Shield in Ontario (Percival and Easton, 2007). The report expands the understanding of the geology since the 1992 compilation provided by the Ontario Geological Survey in *Geology of Ontario*, and includes data and interpretations produced through several recent geologic development initiatives: Operation Treasure Hunt, Discover Abitibi, Abitibi-Grenville and Western Superior Lithoprobe transects, Western Superior National Mapping Program (NATMAP) transects, and several revised maps and data sets.

In addition, the report contains digital geology and geophysical maps, containing data point distributions from published databases of geochronology, litho geochemistry, drill-hole locations, and earthquake magnitudes and locations.

4.2.2 Seismic Response of Underground Structures

The seismic response of an underground structure, such as a Deep Geological Repository (DGR), is a function of the ground motion characteristics that develop at depth following a seismic event. Evidence and case histories show 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). However, because there is a lack of actual subsurface motion data, current seismic design practices are based on ground motion characteristics measured at the surface and do not take advantage of attenuation with depth, which could lead to an overestimation of the seismic loading.

In late 2006, NWMO initiated a multiphase seismological study with Dr. Gail Atkinson of Carleton University/University of Western Ontario to quantify the variation of seismic ground motion response with depth through field measurements at the Sudbury Neutrino Observatory (SNO) site beneath the Inco Creighton Mine in Sudbury, Ontario (Figure 4.1). Five, three component broad band oriented seismographs were installed at different depths and at the surface (two units at ground surface, one unit at the 4600 ft level and two units at the 6800 ft level).



Local events recorded at the site during 2006/2007 are shown on Figure 4.2. All events recorded at surface and subsurface stations were analyzed. The primary findings indicate that ground motions measured appear to be lower at underground sites than on the surface (Atkinson and Kaka 2007). There is also a greater difference between the horizontal and vertical component amplitudes for surface sites than those underground due to near-surface velocity gradient effect. The inferred high-frequency decay parameter estimated from these

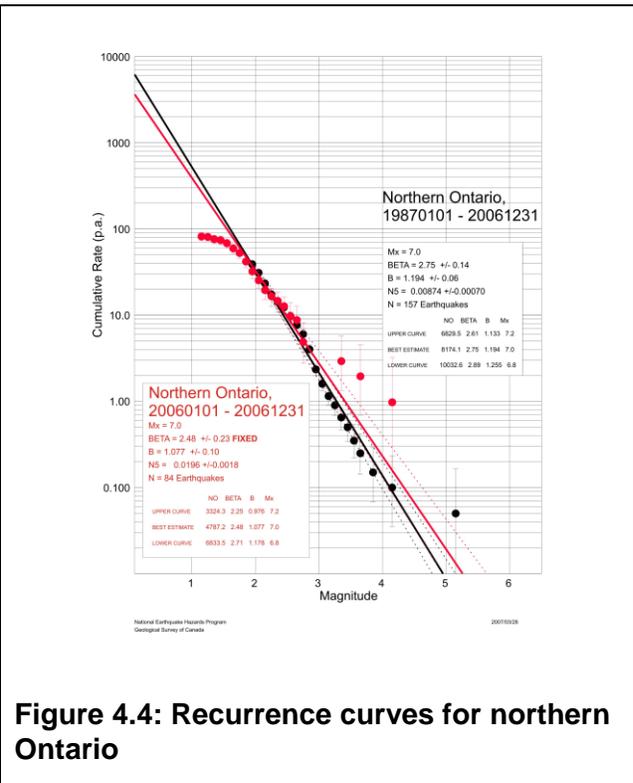
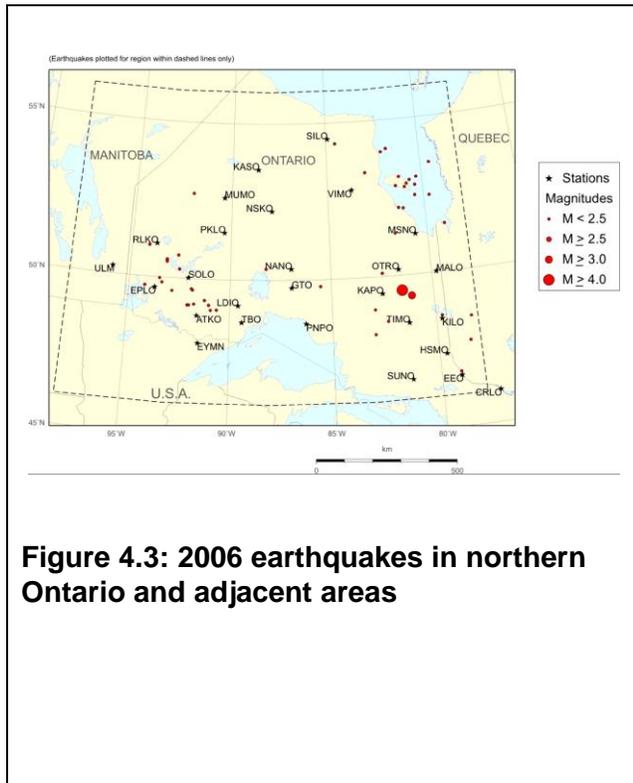
small local events is larger than expected – about 0.05 for surface sites and 0.03 for underground sites.

4.2.3 Seismic Monitoring

In 2007, the Canadian Hazards Information Service (CHIS) of the Geological Survey of Canada (GSC) continued to conduct monitoring of the low levels of background seismicity in the northern Ontario and eastern Manitoba portions of the Canadian Shield. CHIS maintains a network of twenty-six seismograph stations to monitor these regions.

During the 2006 period 83 earthquakes were recorded ranging from magnitudes (m_N) of 1.2 to 4.2 (See Figure 4.3). The largest of these events occurred in the Cochrane-Kapuskasing region of Ontario with magnitudes of 3.4, 3.7 and 4.2. The most westerly event was a 2.2 m_N event located near Kenora, Ontario. The 83 events recorded in 2006, compares with 103 events in 2005, 79 events in 2004, 45 located events in 2003, and 45 events in 2002. The general increase in recorded events is a reflection of the lower threshold due to increased station density in the northern part of the province. The magnitude location threshold has decreased in this region of the country from about m_N 3, to approximately m_N 2.5 or even lower in many areas.

The magnitude-recurrence plots for the year 2006 earthquakes are compared to the 20-year period of 1987 to 2006 inclusive as shown on Figure 4.4.



4.2.4 Matrix Pore Fluids in Crystalline Shield Rocks

In the crystalline rock of the Canadian Shield and in low permeability sedimentary rock such as clays or shales, groundwater occurs mainly in permeable fractures and fault zones and in pore spaces between individual grains in the rock (matrix pore water). At the depths considered for a repository for used nuclear fuel where fractures are infrequent, pore water is the most important form of groundwater in both crystalline and sedimentary rock environments. Knowledge of pore water compositions is required for near-field performance and safety assessment calculations and for models involving groundwater transport or evolution.

Beginning in 2005, a collaborative work program was undertaken to develop a protocol for determining the elemental and isotopic compositions of pore waters in deep crystalline environments from core samples which could be complete within a 3 to 6 months time period after drilling. Several methods to determine pore fluid composition from freshly drilled core were investigated and compared, including crushing and leaching of the core, measuring the composition of water diffusing out of the core ('out-diffusion'), displacing fluids from the core using high speed ultracentrifuge methods, and collecting seepage waters from underground boreholes. Of the methods investigated, the ultracentrifugation technique showed particular potential, because it can be used to rapidly and directly extract pore waters for determination of chemical and isotopic compositions.

A new one year research program was initiated in 2007 to investigate the feasibility of the ultracentrifugation method for application to sedimentary rock. This research includes i) a review of the ultracentrifugation technique as previously applied to different rock types; ii) application of the method to freshly-drilled limestone core from the Bowmanville Quarry in Ontario; and iii) the development and documentation of a protocol for the extraction and analysis of matrix pore water from carbonate rock using this method. The preliminary results from this study demonstrated that it was possible to extract small quantities (<0.5 ml) of pore water from the low porosity limestone samples. However, the chemical compositions and salinity of the extracted pore water were found to vary with subsequent extractions on the same core. Further testing of the ultracentrifugation method is required to demonstrate that the determined pore water compositions are representative of the in-situ pore waters when applied to either sedimentary or crystalline rock.

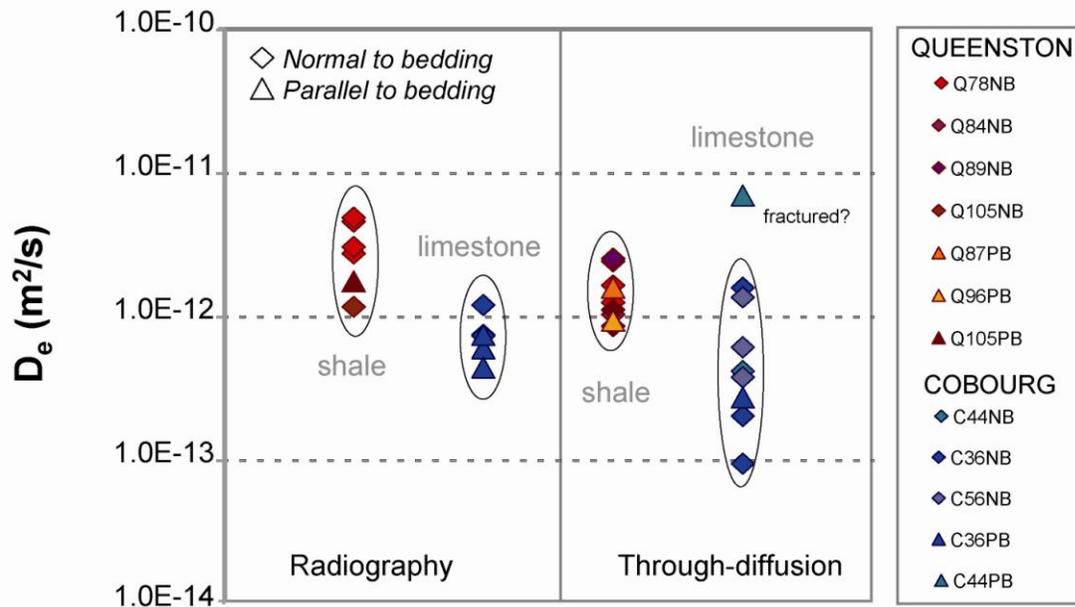
4.2.5 Diffusion in Sedimentary Rock

Within low permeability sedimentary formations, diffusion is expected to be the dominant solute transport mechanism. Predictions of mass transport by diffusion require information on the rock properties including porosity, pore geometry, pore interconnectivity, effective diffusion coefficients and permeability. Standard investigation techniques such as through-diffusion measurements, which are used to estimate bulk values of porosity, rock capacity factor, and an effective diffusion coefficient, provide a single bulk measurement for these parameters in each sample. The development and testing of experimental protocols to characterize the bulk diffusive and mass-transport properties of rock matrices using standard through-diffusion measurements were described by Vilks and Miller (2007).

To study diffusive transport and evolving reactivity in sedimentary rock (sandstone, limestone and shale), an X-ray radiography technique for characterizing and quantifying the concentration distribution of an iodide tracer solution in rock samples is being developed and tested by the

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

A comparison of the through-diffusion and 1-D X-ray radiography technique was undertaken, 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. Similar values for the effective diffusion coefficient (D_e) were determined using the radiography and through-diffusion methods (Figure 4.6).



Note: The designation NB in the sample label indicates measurement made normal to bedding; PB indicates measurement made parallel to bedding.

Figure 4.5: Comparison of effective diffusion coefficients estimated by radiography (Cavé et al., in prep.) and measured by the conventional through-diffusion technique (Vilks and Miller, 2007).

Both the through-diffusion and the X-ray radiography methods are examples of laboratory-scale techniques for the measurement of the diffusive transport properties. Analysis of natural environmental tracer profiles (such as chloride, bromide, iodide, the stable isotopes of oxygen and hydrogen and noble gases such as He) in the pore waters of low-permeability sedimentary rocks can be a powerful approach for assessing the transport properties of potential host rock formations for nuclear waste management (e.g. Gimmi et al., 2007; Bigler et al. 2005; Patriarche et al. 2004a,b; Rübel et al. 2002) at geologic spatial and temporal scales. Examination of the concentration patterns of natural tracers in pore waters, which have developed through geologic time in the rock matrix of a sedimentary sequence, provides an

opportunity to i) assess the relative influence of advective and diffusive transport mechanisms; ii) estimate the formation-scale transport properties, especially diffusion coefficients and travel times; and iii) compare the formation scale parameters with those determined at smaller scales (e.g. diffusive properties measured at centimetre-scale in the laboratory) (Gimmi et al. 2007).

4.2.6 Hydrogeochemical Synthesis

The published geochemical database for groundwater from sedimentary formations underlying southwestern Ontario and eastern Michigan has been expanded to include geochemical information collected during over 25 years of research at the University of Waterloo. Chemical and isotopic ($\delta^3\text{H}$, $\delta^2\text{H}$, $\delta^{18}\text{O}$ and $^{87/86}\text{Sr}$) analyses for more than 200 groundwater samples were compiled to characterize groundwater in three-dimensions on a regional basis. In 2007, the evaluation of evidence relating to the evolution and stability of the groundwater systems over geological time scales continued, through a synthesis of database with published geological, hydrogeological and geochemical literature. This evaluation focuses on evidence related to i) potential pathways of groundwater transport and mixing within the Palaeozoic sequence; ii) the extent of cross-formational flow; and iii) the depth of penetration of modern recharge and cold-climate (glacial) waters into the Paleozoic sequence.

Chemical and stable water isotope ($\delta^{18}\text{O}$, $\delta^2\text{H}$) signatures of shallow (<150 meters) groundwaters from Devonian, Silurian and Ordovician-aged formations are indicative of recharge of modern meteoric waters. Only a few of these groundwaters taken from within Devonian-aged formations were found to have isotopic signatures consistent with glacial recharge. Deep groundwaters (>150 meters) sampled from oil and gas reservoirs in formations of a specific age and rock type (e.g. Ordovician-aged limestone or Silurian-aged sandstone) generally have stable isotopic signatures ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) which are clustered and unique, with little overlap in the ranges, which suggests that cross-formational flow is limited. The chemical compositions of these groundwaters are consistent with evolution of the groundwaters by the evaporation of seawater past halite precipitation. Increased concentrations of non-conservative elements such as Ca, Sr and decreased Na and Mg relative to that expected for degree of evaporation is indicative of water-rock reactions and suggests long residence times for these waters. The strontium isotopic signatures of waters sampled within Silurian-aged evaporites are consistent with the Sr isotopic signature of seawater during the Silurian. Groundwaters from all other formations have signatures which are enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ relative to seawater at the time the formations were deposited, which is also consistent with long residence times.

4.2.7 Geographic Information Systems

One of the strategic objectives of the NWMO is the development of a collaborative siting process to identify potential candidate sites for the long-term management of used nuclear fuel in a suitable geological formation in an informed and willing host community. The site evaluation/selection process will require the use of a large volume of digital spatial data that need to be managed in an efficient and traceable manner. The advantage of spatial data is its geographic reference and spatial relationships that allow for querying data by location and generating visual products. In 2007, the NWMO completed an initial phase of a project with the objective of enabling Geospatial Information Technology (GeoIT) to support the siting process activities.

The acquisition of readily-available, open source, spatial data was the focus of this project. Project activities included:

- Outlining a conceptual framework of the NWMO GeoIT system.
- Investigating and acquiring base mapping data at small scale (~ 1:1Million) across Canada for key features such as transportation, geopolitical boundaries, water bodies and settlements.
- Obtaining more specific detailed spatial data at larger scales for the four nuclear provinces (Ontario, Saskatchewan, Quebec, and New Brunswick) with mapping scales ranging from 1:250,000 – 1:10,000.
- Outline a Quality Assurance process to manage and maintain the GIS data.

Over 300 individual geospatial layers were gathered, inventoried and categorized into several themes including geopolitical, infrastructure, settlements, geology and environment. Further development is planned for 2008 with a focus on user interfaces with the data repository.

4.3 LONGTERM GEOSPHERE STABILITY

4.3.1. Glaciation Impacts on Flow System Evolution

A primary consideration in assessing the performance of a repository for used nuclear fuel in Canada is the ability of a deep geological repository to withstand appreciable perturbations to the sub-surface hydrological regime. Among the most intense of plausible perturbations is that associated with re-glaciation of the northern part of the North American continent. During the latter half of the Pleistocene period, nine glacial events, each with quasi-periodic cycle of 100,000 years, have significantly altered the landscape of Canada. The explanation for the recurrent sequence of glaciation events is widely understood to be caused by the so-called "Milankovitch effect". Small changes in effective solar insolation caused by the changing geometry of Earth's orbit around the Sun are highly significant and have induced the recurring continental scale glaciation events on the approximate 100,000-year timescale.

The University of Toronto Glacial Systems Model (UofT GSM) has been previously applied as part of the NWMO's Technical Program to construct a suite of equally plausible models of the continental-scale, glaciation-deglaciation process that are able to satisfy observational constraints. The results of the 100-kyr simulations included the magnitude and time rate of change of Laurentide Ice Sheet thickness, ground surface temperatures, permafrost depth, meltwater production and other attributes that were relevant to a Canadian Shield setting (Peltier, 2006). The time-dependent, surface boundary conditions were considered appropriate as input to sub-surface hydrology models.

In 2007, the UofT GSM was further applied to explore the time-dependent nature of surface boundary conditions that would be representative of a southern Ontario setting. Because southern Ontario is located near what was the southern edge of the Laurentide ice-sheet during its sequence of Late Quaternary expansions, it is a region of strong temporal variability in glaciation processes. A final report will be issued in 2008 including: 1) an updated review of the current state of understanding of the processes of Long Term Climate Change related to glaciation processes; 2) descriptions of 8 models of continental-scale glaciation-deglaciation who's characteristics provided acceptable fits to the totality of the observational constraints; and 3) time series of the evolution of a number of specific model predictions at a particular location in southern Ontario. The models and resulting time series are characterized by 3 main phases

of advance and retreat within the 100-kyr cycle, illustrating the important role that orbital obliquity forcing plays in controlling the growth and decay of ice-cover.

4.3.2. DECOVALEX THMC Task E Glaciation

The effects of long-term climate change within a sub-regional Shield domain were explored as part of the international DECOVALEX project (DEvelopment of COupled models and their VALidation against EXperiments in nuclear waste isolation). Task E of DECOVALEX THMC (Thermal-Hydraulic-Mechanical-Chemical processes) (www.decovalex.com) was initiated in 2004 as a 3-year work program intent, in part, on examining the coupled THMC effects of a glacial cycle on groundwater flow system dynamics at time scales relevant to repository performance (about 100,000 years). The primary purpose of Task E was to provide a reasoned basis to support the treatment of long-term climate change in performance assessment and an overall safety case for a deep geological repository.

Systematic, 2-dimensional and 3-dimensional THM simulations with varying degrees of coupling, including depth dependent salinity (represented as a change in groundwater density) and temperature dependent density and viscosity, were undertaken using the MOTIF finite-element code. The modelling domain for the THM simulations consisted of a 1.6-km deep sub-regional scale ($\approx 100 \text{ km}^2$) fractured Shield flow system and transient boundary conditions were developed from two realizations (representing cold-based and warm-based glacier conditions) of the University of Toronto Glacial Systems Model (GSM) of the last North American continental glaciation. The GSM simulations included transient normal stress and temperature boundary conditions, as well as basal ice sheet meltwater production rates, for 120,000-year period.

Deep geological repository performance related issues addressed by this Task E case study included the infiltration of glacial meltwater to the subsurface, generation of anomalous hydraulic head and evolution of the effective state of stress during a glacial event. The impact of various model parameters were also investigated including the degree of coupling of THMC (salinity) processes, the surface boundary conditions (ice-sheet topography), model dimensionality, and the two alternative glacial scenarios. In addition, a limited numerical study was conducted to simulate groundwater flow dynamics under permafrost conditions.

Some key findings related to deep geological repository performance were:

- i) During glaciation, the evolution of equivalent freshwater head (hereafter referred to as “head”) in the Shield subregional flow system follows the advance/growth and retreat/decay of the ice sheet. For this particular conceptual model, the flow domain appears to have little memory of previous glacial cycles, with respect to carryover of significant thermal and hydraulic effects.
- ii) The increase of hydraulic head under ice loading is not equal to the total stress imposed by the glacier. Consolidation effects increase the head by about 1/3 of the normal stress that the ice sheet imposes on the bedrock, in part due to the ratio between the compressibilities of the rock and the water.
- iii) Sensitivity analyses showed that a temperate glacier, very low permeability rock ($\sim 10^{-20} \text{ m}^2$) and less well connected fractures are necessary for residual hydraulic heads to persist at depth for thousands of years following de-glaciation.

- iv) During the glacial cycle, Darcy flux magnitudes (absolute values) fall into two groups: (i) values on the order of 10^{-2} to 10^{-1} m/a in the fracture zones at various elevations and in the permeable rock mass near surface, and (ii) values between 10^{-7} to 10^{-5} m/a in the rock mass at depths 350 m or more below ground surface. These latter values are representative of diffusion-dominated transport environments. It is important to note that in the conceptual model, FZ permeability was assumed to be constant with depth.
- v) Based on water-coincident particle-tracking analysis associated with meltwater production periods from the GSM realizations, approximately 72% of glacial meltwater particles did not recharge below the bottom of the shallow rock unit at 70m below surface and less than 6% penetrated to the 500-m level and beyond.

A final report on DECOVALEX THMC Task E summarizing the key findings from all coupled process simulations and implications for performance assessment will be issued in 2008.

4.3.3. Sub-Regional Shield Groundwater Flow System Analysis

Numerical geoscientific methods are being developed to advance the prediction of groundwater flow and mass transport in fractured crystalline Canadian Shield settings. In this context, a key objective of the Regional Shield Groundwater Flow System Analyses work program is to develop a reasoned understanding of groundwater flow system evolution over time scales relevant to repository safety. The characterisation of such flow domains is achieved through an iterative or stepwise process through which multi-disciplinary lithostructural, hydrogeologic, paleohydrogeologic, geophysical, hydrogeochemical and geomechanical data are gathered and then combined into a coherent conceptual descriptive site model(s). At each successive stage of development, data are used to query and test the conceptual model understanding and, if required, to make modifications. As part of this process, numerical flow system analyses offer a systematic framework in which these site-specific data may be integrated and then assessed for consistency. Such performance assessment analyses can instill confidence in the conceptual flow system model(s) and provide a basis for predictive modelling of long-term flow system evolution and repository performance. These aspects of applied numerical methods are explored in this work program.

In Normani et al. (2007), the results of both uncertainty and insight analyses using the FRAC3DVS flow and transport numerical code within the hypothetical, 84 km², sub-regional Canadian Shield flow system were summarized. This case study provides valuable insight into the behaviour of flow domains containing complex, 3-dimensional, curvilinear fracture networks. The impact of uncertainties inherent to site characterization activities was examined by incorporating stochastic parameters into the geosphere model such as:

- a) 100 realizations of equally-probable Fracture Network Models constrained to surface lineaments and fracture statistics;
- b) spatially-correlated, depth-dependent permeability fields in the fracture zones and rock matrix continua;
- c) variable fracture zone width; and
- d) variable fracture zone porosity.

In addition to the influence of fracture zone geometry uncertainties, further numerical analyses were conducted to demonstrate the influence of fresh-saline-brine groundwater distributions as well as the impact of transient hydraulic boundary conditions associated with both cold-based and warm-based glaciation scenarios (Peltier, 2006).

Case study findings include the application of time domain probability techniques to obtain estimates of advective-dispersive-diffusive groundwater travel times, or lifetime expectancies, given flow domain characterisation uncertainty. Figure 4.6 shows the distribution of mean lifetime expectancy (MLE in years) at various depths computed for 100 Fracture Network Model realizations for the hypothetical sub-regional flow system. Regardless of the uncertainty in fracture network geometry, the case study shows that there are large domains in the model with MLEs at or greater than 1 million years.

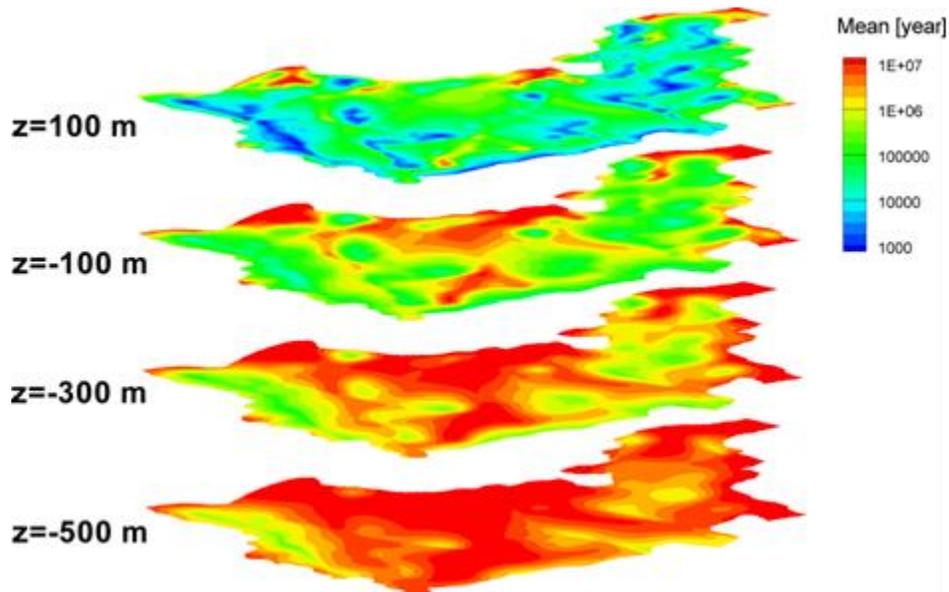


Figure 4.6: Mean (groundwater) lifetime expectancy distribution computed for 100 fracture zone realizations

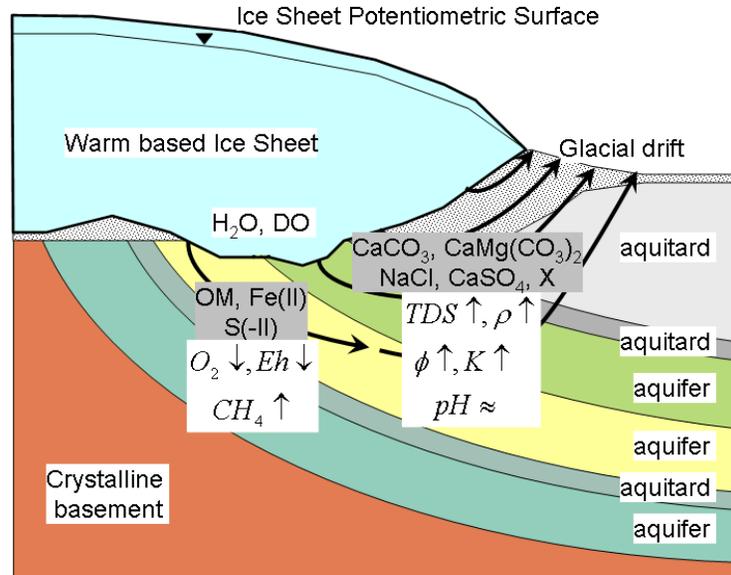
4.3.4. Impacts of Climate-Change on Redox Stability

Understanding the effect of the altered physical and chemical boundary conditions, associated with glaciation/deglaciation processes, on the redox conditions at the repository horizon is an important aspect in assessing long-term geosphere stability. Multiple approaches are used to investigate redox stability. Paleohydrogeological studies in which field and laboratory observations are combined, investigate the presence or absence of weathering signatures in minerals adjacent to fractures in crystalline rock to provide information on the maximum depth of penetration of oxygen carried by recharging groundwaters in the past (e.g. Cavé and Al 2006; Gascoyne et al. 2004; McMurry and Ejeckam 2002).

Numerical models can also be used to simulate the long-term evolution of hydrogeochemical conditions at repository depths. In fractured, crystalline rocks, reactive transport modelling was used to investigate scenarios that depend on coupling physical, chemical and biological

processes of direct relevance to redox conditions (Spiessel et al. 2007; Spiessel et al. 2006). 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 has not been previously used to assess these processes in sedimentary rocks. However, modelling studies of seawater ingress and CO₂ sequestration in sedimentary rocks show promising results, suggesting that modelling of the geochemical evolution in a 2D-subsection of a sedimentary basin is a realistic goal. Figure 4.8 illustrates the conceptual model that was developed to identify the relevant transport and reaction processes that control pore water evolution and composition (Mayer and MacQuarrie, 2007).

Although there are advanced multicomponent reactive models that consider a wide range of the required processes including aqueous speciation, ion exchange, mineral dissolution-precipitation, microbially-mediated redox reactions, density coupling between flow and reactive transport, as well as porosity and permeability changes, it was found that none of the currently available codes are capable of capturing all processes of relevance. Recommendations were made to further improve the capabilities of the reactive transport modelling code (MIN3P) to include a) the Pitzer ion interaction model, b) a modified formulation for microbially-mediated reactions that accounts for inhibition as a function of salinity, c) a formulation for multicomponent and species-dependent diffusion, and possibly d) discretization methods that facilitate the generation of unstructured grids that are better capable of dealing with irregular geometry and outcropping aquifer and aquitard units. The improved code could then be used to investigate a series of conceptual models for recharge of glacial waters in sedimentary basins, and within the context of these models, to evaluate the effect of parameter uncertainty with respect to recharge penetration depth, redox stability and salinity evolution.



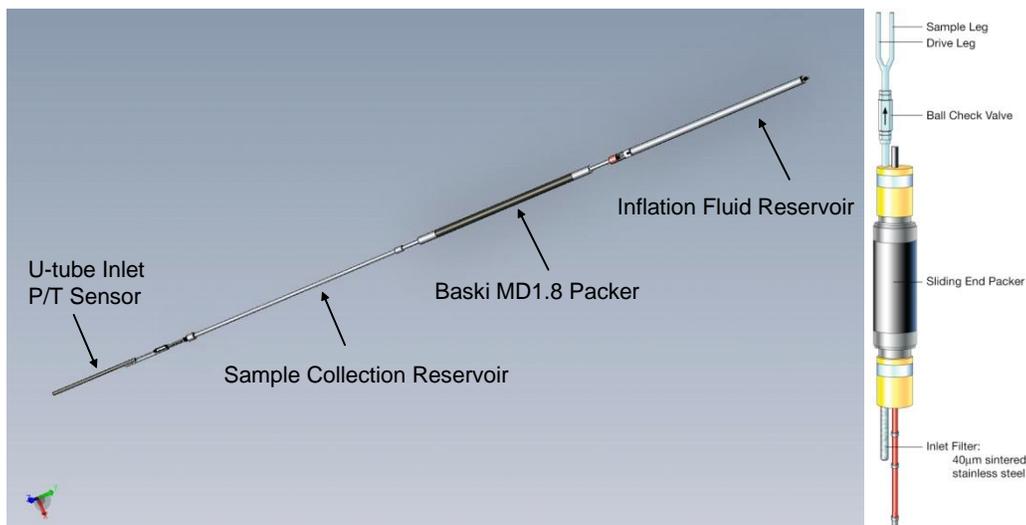
Note: High hydraulic gradients cause enhanced recharge of melt water containing high dissolved oxygen (DO). Carbonate and evaporite mineral dissolution causes an increase in TDS and fluid density, possibly associated with porosity and permeability increase. The presence of reduced mineral phases and organic matter (OM) causes oxygen consumption, possibly sulfate reduction and methanogenesis. Solid phase constituents are shown in grey boxes (from Mayer and MacQuarrie, 2007).

Figure 4.7: Conceptual model for groundwater evolution in response to melt water ingress.

4.3.5. Impacts of Permafrost

The scientific understanding of permafrost and its role in influencing flow system evolution and fluid movement in Shield terrain is being advanced through the International PERMAFROST project (Geological Survey of Finland, Posiva, SKB, NASA, NWMO and Nirex). NWMO participation in the project provides geochemical expertise in the sampling and interpretation of groundwaters and gases relative to flow system dynamics in permafrost environments. In the first three phases of the project, research was conducted at the Lupin Mine site in Nunavut, Canada (Frape et al. 2004; Pannenen and Ruskeeniemi 2003; Ruskeeniemi et al. 2003; Ruskeeniemi et al. 2002). Field investigations at a new site in High Lake, Nunavut, Canada (Zinifex Ltd.) began in 2006 and provide an opportunity to collect hydrogeochemical information from a site which is undisturbed by mining activities for comparison with the Lupin Mine site. The High Lake site is located within 50 km of the Arctic coast and is situated in within the High Lake greenstone belt.

In the summer of 2006, drilling was conducted to extend an existing shallow exploration borehole to a depth of 480 m, below the base of the permafrost. Field activities in 2007 commenced with drilling to remove ice which had formed in the borehole since the previous summer. A Deep Borehole Assembly (DBA) was then installed in the borehole, which contained a pneumatic packer, U-tube sampling system with a sampling reservoir and a temperature/pressure monitoring system (Figure 4.9). High quality measurements of physical properties (hydraulic conductivity, groundwater elevation and temperature measurements) were obtained using the DBA during the 2007 field season. With further modifications to prevent the sample lines from freezing, collection of high quality chemical samples will likely also be possible under permafrost conditions using the DBA.



Note: DBA designed by Barry Freifield (Lawrence Livermore National Laboratories).

Figure 4.8: Cross-section of Deep Borehole Assembly (DBA), showing each section and an inside view of the packer and sampling system.

4.4 NUMERICAL TOOLS AND METHODOLOGIES

4.4.1 Enhancements to FRAC3DVS-OPG

As part of the NWMO's program to further advance the numerical simulation of flow and transport in deformable, fractured porous media under variable density and non-isothermal conditions, a number of modifications to FRAC3DVS-OPG were completed in 2007. These modifications and associated application examples were summarized in Guvanasen (2007) and included:

- i. coding and application of a previously developed sub-gridding technique;
- ii. developing and implementing an approach to better account for the effects of hydromechanical coupling on flow system dynamics as affected by the passage of a glacial front, and
- iii. incorporating anisotropic molecular diffusion coefficient.

With the code modifications to incorporate the subdiscretization methodology into FRAC3DVS-OPG completed (Guvanasen, 2007), the task of subgridding has become more efficient and practical. The pre-processor for FRAC3DVS-OPG was modified to include a grid generator that can generate imbedded subgrids. The generator assumes that the current grid is the parent grid and resolution refinement in a certain area is required. However, the user can incorporate an externally-generated, multiple-level, successively-refined grid through a grid input file. The host rock surrounding a deep geological repository may be subjected in future to glacial stresses, which in turn can induce changes in groundwater flow patterns and transport paths as a result of thermo-hydro-mechanically coupled processes. Since FRAC3DVS-OPG currently does not have the mechanical component to link to its flow and heat transport components, the code was modified to accommodate the purely vertical strain case only (areally homogeneous vertical stress), following Neuzil (2003). Options for adding a mechanical module will be investigated in 2008.

Anisotropic porous media have different diffusion properties in different directions. In compacted or consolidated sedimentary deposits, pore geometry tends to be directionally dependent, thereby resulting in anisotropic molecular diffusion. Since FRAC3DVS-OPG originally assumed that molecular diffusion was isotropic, a formulation for anisotropic molecular diffusion was developed. Based on this formulation, FRAC3DVS-OPG was modified to accommodate anisotropy in molecular diffusion.

4.4.2 FRAC3DVS-OPG Quality Assurance

The increasing importance of FRAC3DVS in repository performance and safety assessment has made it essential that the code be maintained, modified, tested and documented in a formal and disciplined manner. With this objective in mind, a work program was undertaken jointly between HydroGeoLogic Inc. and the University of Waterloo to ensure that a version of FRAC3DVS, entitled FRAC3DVS-OPG, meets the quality assurance requirements for modifying and maintaining software such as OPG NWMD's W-PROC-EN-0005 and the Canadian Standards Association N286.7-99 entitled "Quality Assurance of Analytical, Scientific, and Design Computer Programs for Nuclear Power Plants." Specifically in 2007, a peer review of a draft FRAC3DVS-OPG QA document, which includes a theory manual, a validation report and a user manual, was completed. A beta version of FRAC3DVS-OPG v.1.0 was developed and released in 2007 along with a comprehensive collection of test cases.

4.5 INTERNATIONAL PROJECTS

4.5.1 Quarried Block Experiment – Bentonite Colloid Transport

The Äspö Hard Rock Laboratory Colloid Project is evaluating the potential ability of bentonite colloids, released from repository buffer and backfill materials, to facilitate radionuclide transport in Äspö groundwater. In 2007, the NWMO in collaboration with SKB, continued to support the bentonite colloid transport experiments at AECL's Whiteshell Research Laboratory using the Quarried Block (QB) sample, a 1 m x 1 m x 0.7 m block of granite containing a single, complex, but well characterized, through-going, variable aperture fracture (Vilks and Miller, 2006). The purpose of this laboratory-scale experimental program was to improve on the understanding of physical retardation processes that effect bentonite colloid mobility in crystalline rock fractures.

Bentonite colloids form a polydisperse solution with particle size distributions that can range from a few nm to approximately 2 microns. Through the use of an Ultrafine Particle Size Analyzer (UPA) and a two step analysis process involving the removal of particles larger than 0.1 μm , it was determined that the particle size distributions of the bentonite colloid tracer solutions were bimodal, with peaks at approximately 8 nm and between 200 and 300 nm. A methodology to determine particle size distributions at various points along the elution profiles was developed to better understand the transport behaviour of the polydisperse bentonite colloid tracers.

In 2007, migration experiments were conducted to supplement the results of the 2006 activities reported by Vilks and Miller (2006). The work program included experiments to: i) investigate the transport behaviour of 100 nm latex colloids in saline, Äspö-type water; ii) explore the differences in transport behaviour between mono-disperse and polydisperse suspensions of bentonite and latex colloids; and iii) provide additional colloid transport data over longer transport distances and low transport velocities suitable for future numerical modelling activities by SKB.

Size analysis of the 100 nm latex colloids suspended in the saline solution showed that the latex colloids had formed flocs with an average size of 1.6 μm . This behaviour contributed to significantly different transport behaviour, notably lower tracer recovery, than would be predicted based on behaviour of latex colloids suspended in dilute water.

To explore the transport behaviour of various size fractions within a polydisperse bentonite suspension, a centrifuge based separation process was followed to generate three colloid tracers of increasing size fractions that were separately injected into the QB fracture during tests TT-5, TT-6 and TT-7. The bentonite colloid size distributions within each class are illustrated in Figure 4.9. The percent bentonite recovery was the highest for the injection of the small colloids (90%), and progressively decreased to 81% and 13.7% as the proportion of large colloids was increased within the injected tracer solutions. This behaviour is consistent with previous findings and reinforces the observation that bentonite colloid transport is dominated by the smaller particle sizes that remain in suspension while the larger sizes tend to be retained in the fracture.

The final phase of the work program consisted of opening the QB fracture for post-test analyses that included photographing the distribution of fluorescent latex colloids under ultraviolet light and quantifying colloid deposition on the fracture surfaces using a grid-based swabbing method.

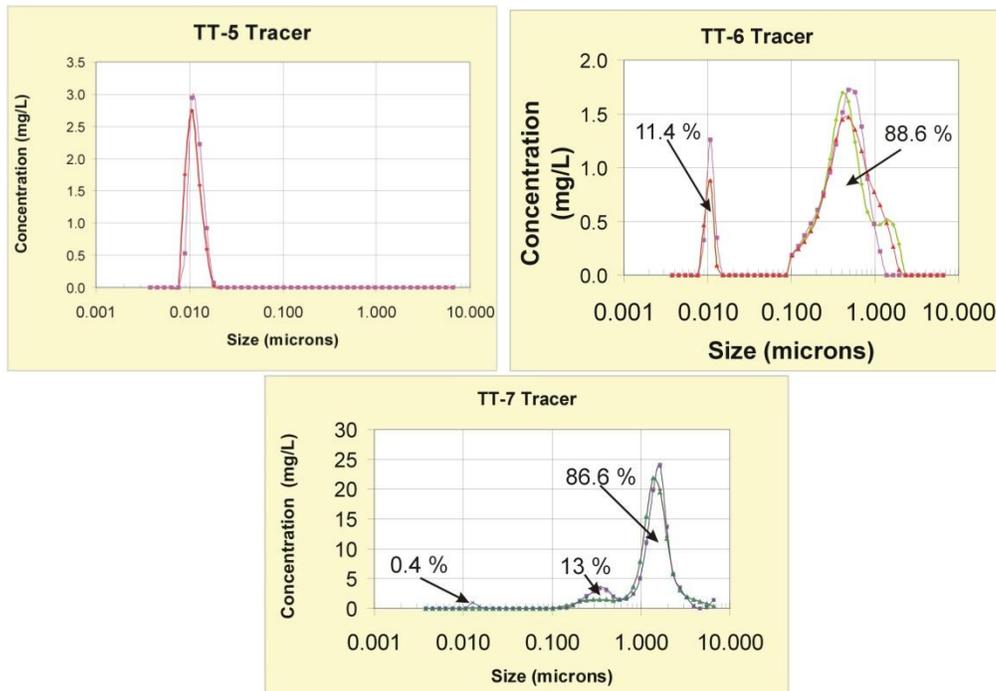


Figure 4.9: Bentonite tracer size distributions used in experiments to evaluate the effect of particle size on bentonite colloid transport.

The final phase of the work program consisted of opening the QB fracture for post-test analyses that included photographing the distribution of fluorescent latex colloids under ultraviolet light and quantifying colloid deposition on the fracture surfaces using a grid-based swabbing method.

Figure 4.10 shows the roughness of top to surface of the QB fracture following separation of the block.

An annual report summarizing the findings of the experimental program will be issued in 2008.



Figure 4.10: View of the top surface of the fracture following separation of the Quarried Block.

4.5.2 Äspö Modelling Taskforce

Canada is participating in the Äspö Modelling Task Force's Task 7. A modelling team from the Université Laval is participating in Task 7, which involves the numerical modelling of hydraulic responses in the fractured crystalline rock environment located on Olkiluoto Island in Finland. A large data set is available associated with investigations for Posiva's ONKALO underground rock characterization facility. The task force also includes modelling teams from Finland, Sweden, France and Japan. Task 7 modelling activities have been subdivided into two related tasks: 1) 7A is focused on simulating a long-term pump test conducted in borehole KR24, which intersects a domain of several large, interconnected, fracture zones; and 2) Task 7B involves simulating hydraulic responses in a series of interference tests completed at a block scale with borehole separations on the order of 10 m and with the intention of characterizing the rock mass between the large 7A fracture zones. One of the unique aspects of the data set is that it includes Posiva Flow Log (PFL) measurements in several open boreholes, both prior to and during the hydraulic tests.

In 2007, the Laval modelling team participating in two task force meetings (TF#22 hosted by SKB in Stockholm, Sweden and TF#23 hosted by the NWMO in Toronto, Canada) and one modellers meeting (hosted by the Chalmers University in Goteborg, Sweden). Modelling activities in the Äspö Modelling Task Force focused on completion of Task 7A and preliminary definition of Task 7B. New FRAC3DVS model development methodologies applied in 2007 allowed for a more realistic representation of 2D irregular fracture zones within a regular 3D mesh and allowed for improved simulations of the KR24 pump test (Figure 4.11).

Simulations for Task 7A have demonstrated the impact of deep, open boreholes whose lengths reach several hundred metres. These open boreholes tend to reduce vertical hydraulic

gradients in the fractured rock mass by enhancing the equivalent vertical hydraulic conductivity. Calibration to both hydraulic heads and observed PFL flow rates in boreholes has proven challenging for all modelling teams. The Laval team has undertaken simulations of travel time probabilities as a useful alternative methodology for the assessment of travel times to surface and illustration of subsurface pathways, which complement the performance assessment related activities within the Task Force.

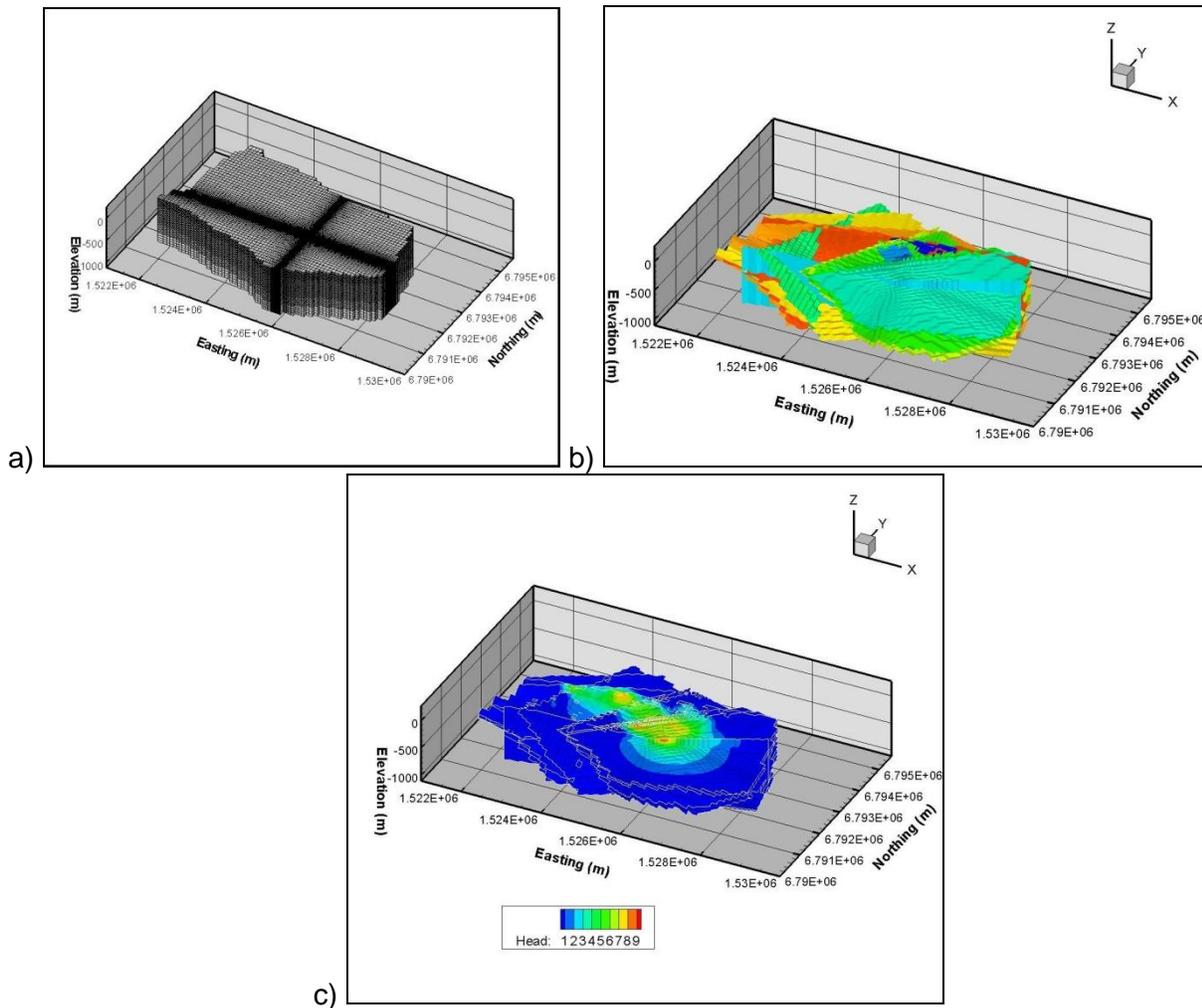


Figure 4.11: Example Task 7A modelling results: a) FRAC3DVS model grid, b) Fracture zone representation as 2D elements and c) head change (m) in fracture zone elements.

4.5.3 OECD/NEA AMIGO Project

AMIGO, an OECD/NEA international project entitled “Approaches and Methods for Integrating Geologic Information in the Safety Case”, was established in 2001 with the purpose of providing a forum for the exchange of international information and experience on the use of geoscience information in the development of a safety case for a deep geological repository.

In an effort to foster awareness of the role of geoscience in the Safety Case, AMIGO undertook to document current international experience with respect to the practical usage, communication and management of geoscientific data and information that underpin an explanation of the geosphere and its evolution relevant to assessing repository concept performance and safety. In 2007, the NWMO led the preparation of an OECD/NEA report summarizing the responses from 17 AMIGO participants, including both implementing organizations and regulatory bodies from 12 countries, to a questionnaire that examined the current status and role of geoscience in contributing to a repository safety case. Participants represent a broad cross section of national programs with a variety of repository concepts in different host rocks and at different stages of development, from conceptual studies to repository siting and licensing.

The report, to be issued in 2008, presents examples of important contributions, discusses challenges that include effective communication of the science and the collaborative effort of different geoscience disciplines, and explores where geoscience might play a further role in studies of long-term safety. The report specifically addresses the emerging role of geosynthesis, which is the reasoned integration of available geoscience information to construct a comprehensive understanding of the geosphere, often documented in a dedicated volume or part of a safety case.

5. SAFETY ASSESSMENT

The objective of the safety assessment program is to be able to evaluate the long-term safety of a deep geological repository for used nuclear fuel. In the near-term, this is addressed through case studies, and through developing and improving our models, data and software. In addition, the safety assessment program can provide feedback to the repository engineering and geoscience programs regarding research directions.

The following sections outline the activities of the work program in 2007. The activities are organised into sections on Repository, Geosphere and Biosphere Modelling, and Case Studies.

5.1 REPOSITORY MODELLING

The 2007 repository safety assessment work focussed on uranium dioxide (UO₂) dissolution studies, calculation of the gamma dose rates in water-filled used fuel containers, and modelling the evolution of the buffer porewater using the thermodynamic code PHREEQC. (Work on container corrosion models was carried out under the Repository Engineering program and is described in Section 3.1.)

5.1.1 Used Fuel Dissolution

The first barrier to release of radionuclides is the used fuel itself. Even if a container fails, most radionuclides remain trapped within the UO₂ grains and are only released as the fuel itself dissolves. Therefore, the rate of fuel dissolution is an important parameter for long-term safety.

UO₂ dissolves very slowly under reducing conditions. In a failed container that has filled with groundwater, used fuel dissolution is expected to be driven by oxidation of the fuel surface by oxidants (particularly hydrogen peroxide, H₂O₂) generated by alpha-radiolysis of water (Wren et al. 2005). Hydrogen gas (H₂) is also generated from radiolysis, but much larger amounts are generated as a result of corrosion of the inner steel vessel of the container.

In 2007, a review of used fuel and uranium dioxide studies was published (Shoesmith 2007). The primary factor controlling fuel dissolution is the redox condition established at the fuel surface by the radiolysis of water, how it evolves with time as radiation fields decay, and how it is influenced by the presence of oxidant scavengers, especially H₂, produced by corrosion of the steel liner in the container.

If the container fails early, and oxidizing conditions are established, the fuel dissolution process will be a corrosion reaction driven by radiolytically-produced H₂O₂. As radiation fields decay and conditions become less oxidizing, the fuel corrosion rate will decrease. The rate will be influenced by the formation of corrosion product deposits, facilitated by calcium and silicate in the groundwater. These deposits could inhibit the corrosion process but could also lead to the formation of locally acidified sites at which the corrosion rate is increased. As redox conditions become less oxidizing, however, these issues become less important. For example, the generation of acidity within deposits is unlikely since the corrosion rate becomes limited by the available concentration of oxidants.

For sufficiently low radiation dose rates, a threshold for the transition from corrosion to chemical dissolution was identified electrochemically and validated by dissolution rate measurements on used fuels and alpha-doped UO_2 specimens (see Figure 5.1). For CANDU fuel this threshold is expected to occur for decay times between 10,000 and 20,000 years (see Figure 5.2). Beyond this threshold fuel dissolution will be solubility-controlled and extremely slow.

Figure 5.1 also indicates that reasonable consistency exists between electrochemically predicted and analytically measured fuel dissolution rates.

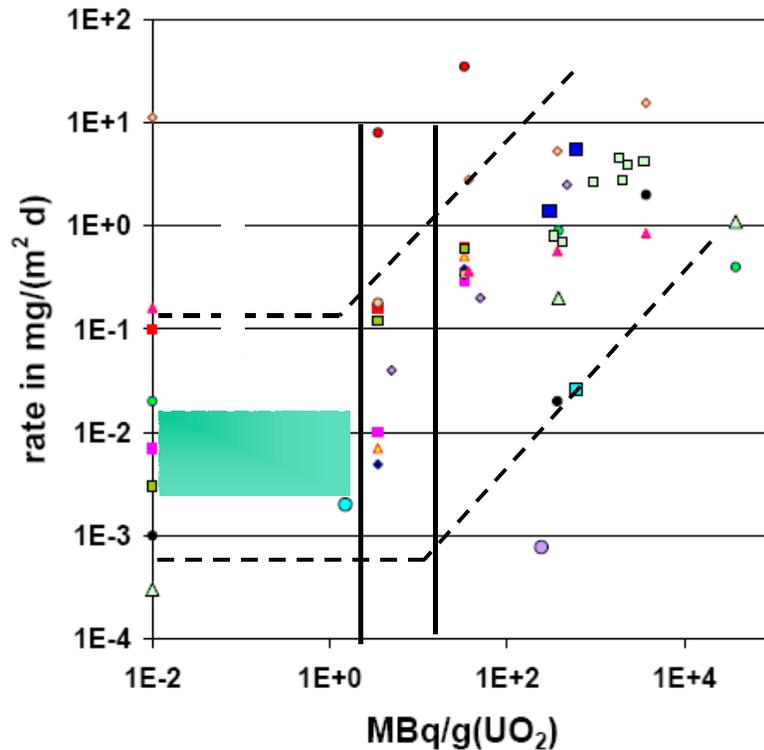


Figure 5.1: Corrosion rates measured as a function of alpha activity on natural UO_2 (10^{-2} MBq/g), alpha-doped electrodes and spent fuel (after Poinssot et al. 2005). The different symbols represent different experimental results. The transition between solubility-controlled and radiolytic control are illustrated by the vertical lines. The shaded zone shows the corrosion rates established electrochemically.

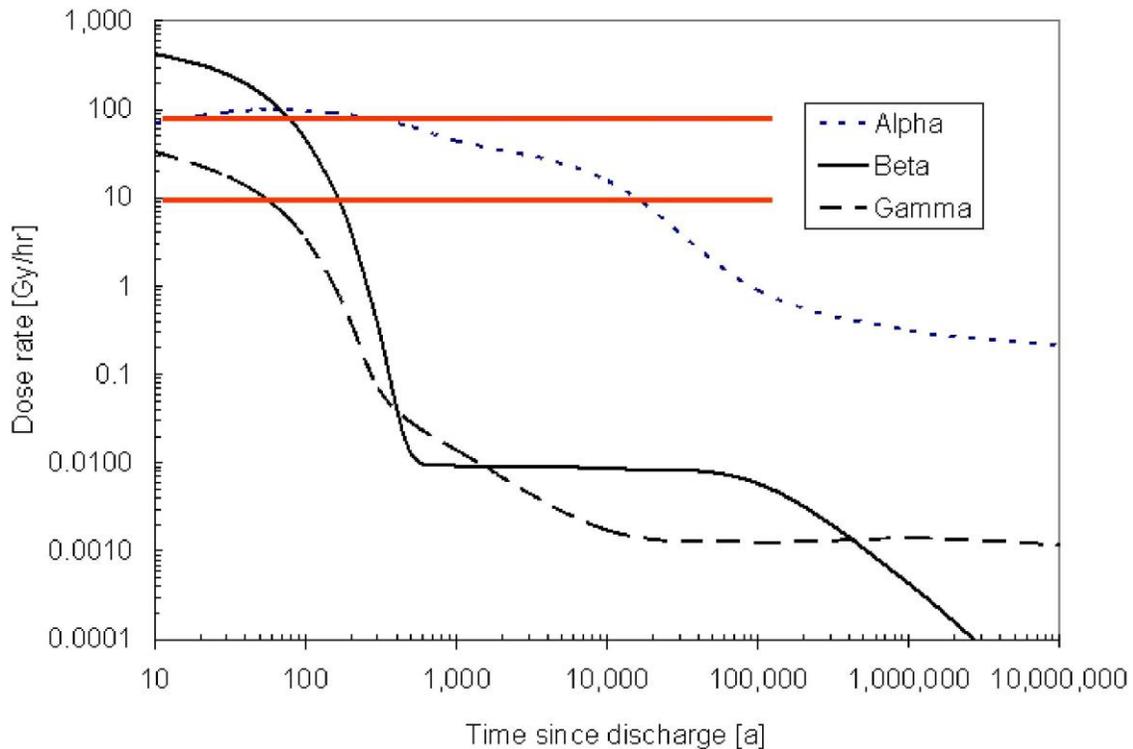


Figure 5.2: Alpha, beta and gamma radiation dose rates calculated as a function of time since discharge, for water in contact with a CANDU fuel bundle with a burnup of 220 MWh/kgU. The two horizontal lines represent the upper and lower limits of the alpha activity threshold as defined by the two vertical lines in Figure 5.1.

The transition from radiolytic corrosion to chemical dissolution can be very rapidly induced in the presence of oxidant scavengers, especially H_2 . Small concentrations of H_2 suppress the redox condition to the threshold even for used fuels with high gamma/beta radiation fields. For sufficiently high concentrations, the establishment of the reversible H_2/H^+ reaction on noble metal epsilon particles can lead to galvanic protection of the fuel against corrosion. Under these conditions fuel dissolution and radionuclide release would be extremely small (Shoemith 2007).

The 2007 experimental program on used fuel dissolution, which was carried out at the University of Western Ontario, investigated: (1) the influence of H_2 , (2) the influence of fission product doping on the reactivity of UO_2 , and (3) the mechanism of the H_2O_2 reaction with UO_2 . Both electrochemical experiments, typically corrosion potential, E_{corr} , measurements on UO_2 electrodes, and surface analytical techniques were used in the investigations (He et al. 2007, Keech et al. 2007). The tests were conducted mainly with unirradiated 1.5%, 3% and 6% SIMFUELS, representing CANDU fuel burnups from about 210 to 800 MWh/kgU. (SIMFUEL is made by doping unirradiated natural UO_2 pellets with non-radioactive elements to replicate the chemical composition of used fuel, including formation of so-called ϵ -particles – alloys of the fission products Mo, Ru, Tc, Pd and Rh.)

Hydrogen Inhibition

In previous years, it has been found that dissolved H_2 could suppress E_{corr} values well below the oxidation threshold of -0.4 V (Broczkowski et al. 2005). That is, H_2 suppresses fuel corrosion. This process has been electrochemically characterized in detail using SIMFUEL specimens with different levels of simulated burnup (Broczkowski et al. 2007, Broczkowski et al. 2006). The E_{corr} on SIMFUEL decreases with the number density of epsilon particles present in the SIMFUEL and surface analyses confirm that the extent of oxidation of the surface decreased as E_{corr} was suppressed. This effect can be attributed to the reversible dissociation of H_2 (to H^\bullet radicals) on the epsilon particles that act as galvanically-coupled anodes within the fuel matrix, thereby decreasing E_{corr} and inhibiting UO_2 oxidation/corrosion.

H_2/H_2O_2 Synergetic Effects

A program was initiated in 2007 to study the synergetic effects of H_2O_2 and H_2 on fuel corrosion. A series of corrosion potential measurements followed by X-ray photoelectron spectroscopy (XPS) examinations of the surface have shown that H_2O_2 and H_2 do react synergistically on a 1.5 atom% SIMFUEL electrode containing epsilon particles. These experiments were conducted in $H_2(5\%)/Ar$ -purged solution in which various concentrations of H_2O_2 (10^{-9} to 10^{-11} mol/L) were added and the corrosion potential (E_{corr}) was followed. As expected, E_{corr} increased rapidly on addition of H_2O_2 but eventually decreased again in the presence of H_2 . When only argon was used as the purge gas, the rise in E_{corr} was not reversed. Subsequent examination of the electrode by XPS confirmed that the oxidation of the surface by H_2O_2 was prevented (or reversed) in the presence of H_2/Ar but not when only Ar was used. These results suggest that the scavenging reaction, $H_2O_2 + H_2 \rightarrow 2H_2O$, is catalyzed on the epsilon particles, which protects the UO_2 from oxidation and corrosion.

Influence of Fission Product Doping

The influence of fission product doping on the structure, composition and electrochemical reactivity of uranium dioxide was studied (He et al. 2007) using X-ray diffractometry (XRD), scanning electron microscopy (SEM/EDX), Raman spectroscopy and X-ray photoelectron spectroscopy (XPS). Experiments were conducted on SIMFUELS with various doping levels (i.e., various simulated burnups). As the dopant level increased, the lattice contracted, suggesting the dominant formation of dopant-oxygen vacancy clusters. Raman spectroscopy shows that the doping leads to a loss of cubic symmetry, possibly associated with tetragonal distortions of the lattice.

Electrochemical experiments show that the corrosion currents, due to the oxidation of the UO_2 to UO_{2+x} and then to dissolved UO_2^{2+} , are suppressed as the doping level increases. This suppression is particularly marked for the 6% SIMFUEL and is not significant for the 1.5% SIMFUEL. This affect is tentatively assigned to the formation of dopant-vacancy clusters that stabilize the fluorite lattice against the tetragonal distortions, thereby reducing the availability of oxygen vacancies which facilitate oxidation and then dissolution. It should be noted that since CANDU fuel is usually discharged from reactor with burnups of around 1.5at%, fission product doping has a marginal to negligible effect on CANDU spent fuel reactivity.

Hydrogen Peroxide Reaction Mechanism

Studies to define the mechanism and kinetics of H_2O_2 reduction on SIMFUEL electrodes in acidic solutions (pH 1 to 6) were undertaken. In previous years, experiments under neutral to slightly alkaline solutions were completed (Keech et al. 2007). It was found that the rate and mechanism of the cathodic reduction of H_2O_2 on SIMFUEL does not change over the pH range 4 to 9. Within this pH range, H_2O_2 chemically oxidizes the UO_2 surface to U^{V} which is subsequently electrochemically reduced. The U^{V} state is incorporated into the oxidized UO_{2+x} surface layer.

For pH values below about 3, H_2O_2 reduction occurs at considerably less negative potentials. This is attributed to the formation of an adsorbed U^{V} state which catalyzes H_2O_2 reduction. However, since the U^{V} state is less stable at these low pH values, it can either be further oxidized to the U^{VI} state (prior to its dissolution as UO_2^{2+}) or cathodically reduced at much less negative potentials than required in neutral solutions. This instability limits the availability of the U^{V} catalytic state and, in contrast for pH values 4 to 9, currents are always well below the diffusion limiting value.

As noted above, the synergetic effects of H_2O_2 and H_2 on fuel corrosion is also being investigated.

5.1.2 Gamma Dose Rates in Water-Filled Used Fuel Container

The reference used fuel dissolution model depends on the rate at which oxidizing species, which drive fuel oxidation and dissolution, are generated by the radiolysis of water near the fuel surface. The rate of radiation energy deposition into the water is therefore a key input (Garisto et al. 2004). In the Third Case Study, estimates of the alpha, beta and gamma energy deposition rates were made by scaling from other calculations (Garisto et al. 2004). However, a more precise calculation was warranted. The alpha and beta dose rates in water adjacent to used fuel elements were explicitly calculated in 2005. In 2007, gamma dose rates to water adjacent to used fuel elements in a water filled used fuel container were determined. Some of the results are shown in Table 5.1. The calculated gamma dose rates were approximately 2-fold larger than those estimated by Garisto et al. (2004).

The results shown in Table 5.1 are for a single fuel bundle. However, the other fuel bundles in the container would be expected to increase the gamma dose rates relative to those calculated for a single fuel bundle. This relative increase in the gamma dose rate is referred to as the F-factor. It was found that the F-factor for the IV-324 HEX fuel container, with 324 fuel bundles, depends on the decay time of the fuel and the location within the container but is essentially independent of the fuel burnup. The range of calculated F-factors is 1.14 (near the perimeter of the container and decay times less than 1000 years) to 1.46 (near the middle of the container and decay times of more than 1 million years). These F-factors are 2 to 3 times smaller than those estimated in Garisto et al. (2004).

Table 5.1: Average gamma dose rates in water within a fuel bundle envelope for two different fuel burnups and various fuel decay times, for a single fuel bundle

Fuel Burnup (MWh/kgU)	Dose Rates in Water (Gy/hr) as Function of Decay Time (years)						
	50 yr.	100 yr.	200 yr.	10 ³ yr.	10 ⁴ yr.	10 ⁵ yr.	10 ⁶ yr.
220	22.9	7.15	0.71	0.0016	0.0017	0.0027	0.0036
280	29.0	9.03	0.89	0.0023	0.0022	0.0033	0.0036

5.1.3 Buffer Porewater Evolution

The composition of the buffer porewater changes as a result of the reactions occurring in the buffer, e.g., the dissolution of ancillary minerals in the buffer, and the diffusion of chemical species into and out of the buffer. One-dimensional chemical-transport calculations, carried out using the PHREEQC thermodynamic code, were used to determine the evolution of the buffer porewater composition for a MX-80 Na-bentonite buffer material in contact with granite groundwater (specifically CS-730 granite groundwater).

The evolution of the buffer and buffer porewater compositions, at the midpoint of the buffer layer (0.5 m thick), are shown in Figure 5.3. This figure clearly illustrates the changes that occur in the buffer over the short-term, i.e., the exchange of Na in the bentonite with Ca, the increase in the Ca porewater concentration, the decrease in the Na porewater concentration, the increase in the Fe porewater concentration and the increase in the pH.

The siderite ($\text{FeCO}_3(\text{s})$), present in the buffer as an ancillary mineral, begins to dissolve relatively rapidly after about 4400 years and has all dissolved after about 7,000 years. The carbonate released as the siderite dissolves is consumed in the formation of calcite and, therefore, the calcite concentration increases as the siderite concentration decreases.

In this case, the evolution of the buffer porewater is complete and the buffer reaches equilibrium with the granite groundwater after about 28,000 years. The time needed to reach this equilibrium depends on the selected value of the intrinsic diffusion coefficients of the ions.

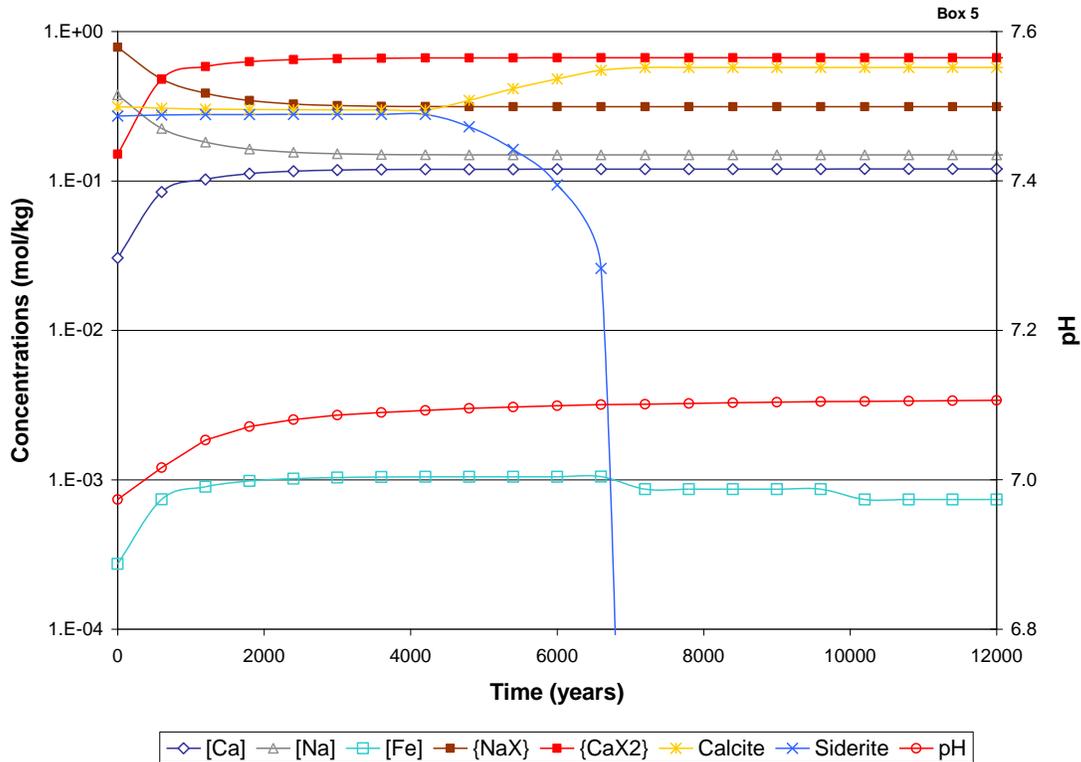


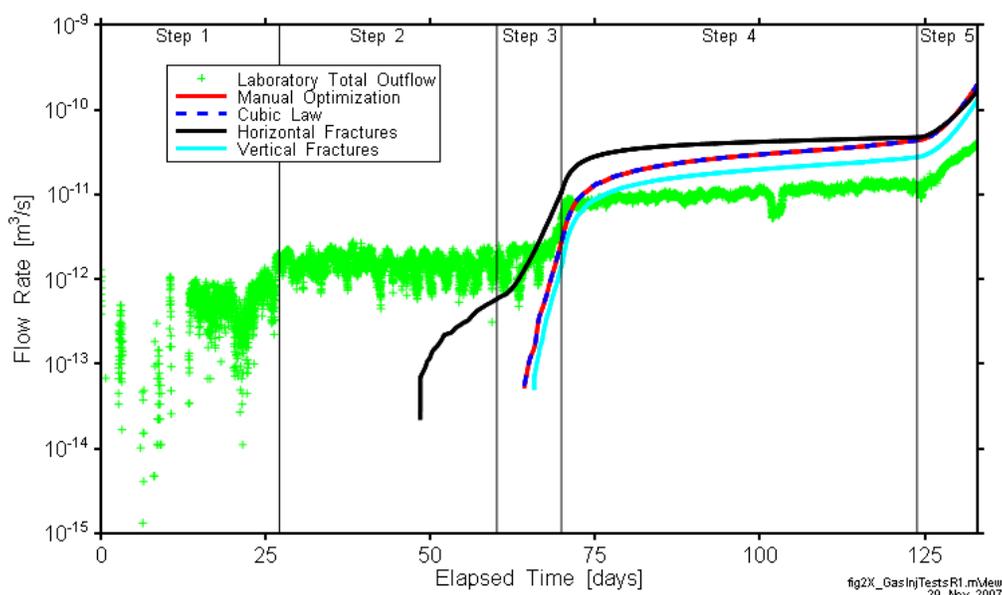
Figure 5.3: Evolution of the composition of bentonite and bentonite porewater at the midpoint of the buffer (with 0.0013 m²/a intrinsic diffusion coefficient).

5.1.4 Gas transport through buffer

Gas may be generated by container corrosion. The low permeability of the surrounding buffer will tend to contain this gas near the container. In order to understand the gas behaviour, NWMO is participating in the Large Scale Gas Injection Test (LASGIT) at SKB's Äspö Hard Rock Laboratory. In particular, NWMO is providing gas transport modelling of the experiment through Intera Engineering, using the TOUGH2 code. Modifications have been done to the code to simulate anticipated gas transport mechanisms, mainly micro- and macro- fracturing of the bentonite, by allowing pressure-induced changes to the bentonite permeability and capillary pressure.

In 2007, the modified TOUGH2 model was applied to the MX-80 laboratory-scale experiment of gas transport in bentonite, as well as to the initial test design analysis for the LASGIT experiment prior to availability of gas testing results.

Modelling of the laboratory model was able to model a gas breakthrough event through the bentonite. Different model options (fracture directionality and heterogeneous permeability field) are capable of improving model results, particularly in distributing the gas outflow as observed in the laboratory experiment (Figure 5.4).



Note: lab outflow prior to Step 3 is primarily liquid.

Figure 5.4: Model gas outflow results comparing the impact of fracture directionality and the capillary pressure function with a laboratory-scale test.

Also, 2007 modelling of the LASGIT test design has examined the sensitivity of the results to certain model parameters. Two-phase flow parameters of importance include bentonite permeability, initial gas saturation, and host rock permeability; modified permeability parameters of importance include the pressure-induced factor and residual liquid saturation for the relative permeability function. Once results of the preliminary gas injection tests are available, our modelling will focus on these parameters and will also examine the influence of fracture directionality and heterogeneous permeability fields in the LASGIT borehole.

In the next few years, results from the full set of gas injection tests will be available. Comparison of our modified TOUGH2 modelling results with the gas injection test observations and with the modeling results from other organizations will increase our understanding of gas transport through bentonite and will improve our modeling capability in future performance assessments.

5.2 GEOSPHERE MODELLING

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

5.3 BIOSPHERE MODELLING

5.3.1 Iodine in the biosphere

Iodine-129 is an important radionuclide with respect to potential long-term impact. In 2002, a review of the literature was completed and key biosphere model parameters were updated for iodine (Sheppard et al. 2002). 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 parameters in the biosphere without resorting to controlled experiments with comparatively large quantities of iodine because of the low sensitivity of standard analysis procedures. A technique was proposed that could allow natural iodine levels to be measured using relatively standard equipment. During 2006, tests of this concept were carried out, and it was demonstrated that natural iodine levels could be measured in a variety of soil and plant samples. The advantage of this approach is that it can allow a wide range of specimens to be collected and analyzed at modest cost. Using natural iodine as an analogue for I-129, this then opens up an opportunity to significantly improve the iodine 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).

Areas within a representative portion of the Canadian Shield were subdivided into distinct sampling zones to ensure the survey represented the physiographical variation within the larger sampling area. Initial results show good agreement between measured transfer factor results and plant/soil concentration ratios for iodine compared to those of Sheppard et al. (2002, 2006); however, more data is required to construct a comprehensive database of iodine transfer factors. A multi-year sampling campaign is under way to collect data from a variety of media and regions, including (future years) agricultural settings.

5.3.2 Non-human biota

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

Work is underway to develop a screening methodology for assessing the potential postclosure radiological impact of a repository on specific representative non-human biota. The methodology involves the estimation of reference No-Effect Concentrations (NECs) for radionuclides in environmental media to which biota are exposed. In this study, NECs were developed for a set of 12 reference radionuclides: C-14, Cl-36, Zr-93, Nb-94, Tc-99, I-129, Cs-135, Ra-226, Np-237, U-238, Pb-210 and Po-210. This list incorporates the major dose contributors identified in the Third Case Study and in other international safety assessments, such as Nagra (2002), ANDRA (2005) and SKB (1999, 2006).

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

assumptions used to derive the NECs, there is confidence that, despite uncertainty in environmental concentrations, there will be no significant ecological effect on biota as long as the NECs are not exceeded. In the event NECs are exceeded, a site-specific Ecological Risk Assessment would be required to determine whether this is due to conservatism in the assumptions, lack of sufficient data or potential real impact. A reference set of NECs is currently being developed and will be available in a 2008 report.

5.4 CASE STUDIES

5.4.1 Software

The postclosure safety assessment of a used fuel repository uses several complementary computer models. These are either commercially maintained codes, or codes maintained under a software quality assurance (QA) system developed at OPG.

Presently, the reference safety assessment data is stored in a custom built text-based format. This ensures that the data is always human-readable and that there is no risk of data loss due to changing commercial code data formats over time. In 2005, we started to convert this text format into a format that meets the international XML data transfer standard. This will ensure that the data can take advantage of this standard and be read by a variety of software tools, including web browsers for example. During 2006 and 2007, the process was continued through modification of standard pre-processors to work with this XML format.

5.4.2 Glaciation Scenario Case Study

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

Our reference time frame for the safety assessment of deep repositories is one million years, roughly equivalent to the time scale for the radioactivity in used fuel to decrease to that due to its natural uranium content. Over the past one million years, the most significant natural event across Canada has been repeated glaciation cycles, which have occurred approximately every 100,000 years. It is possible that current greenhouse gas levels would delay the onset of the next glaciation, but in the long run the glacial cycles are likely to reassert themselves because they are driven by long-term variation in solar insolation due to earth's orbital variations. Thus, for repository safety it is prudent to assume that glaciation cycles will occur in the future. This is also the practice in the radioactive waste management programs in other northern countries, notably Sweden and Finland.

During past glacial cycles, much of Canada has been covered by kilometre-thick ice sheets. Because these glacial cycles represent such a large potential perturbation to a site, the Canadian used fuel disposal program has been examining the implications of glaciation for many years (see, for example, Section 4.3 for recent work in the Geoscience program). The

general conclusion is that an appropriately sited and sufficiently deep repository can provide containment and isolation of the used fuel during glaciation.

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

During 2007, the work focussed on exploring various aspects of the Glaciation Scenario and the development of the tools needed to carry out the safety assessment for a Glaciation Scenario. This work included:

- A description of the stages of a typical glaciation cycle: the temperate, permafrost, ice margin, ice sheet and proglacial lake stages.
- Development and scoping studies of a biosphere model for the Glaciation Scenario. Different exposure groups and pathways are considered for the temperate, permafrost and proglacial lake stages of the glaciation cycle. There are no human receptors at the site during the ice sheet stage.
- Preliminary modelling for the Glaciation Scenario using transient groundwater flow and nuclide transport models to explore the phenomena occurring during ice sheet advance or retreat over the repository site.
- Scoping modelling of meltwater and oxygen intrusion into the geosphere.
- Exploration of modelling capabilities and limitations for representing the changes that occur during a glacial cycle.

The results of the exploratory 2007 work will be used to direct the specific glaciation scenario case study planned for 2008.

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APPENDIX A: LIST OF TECHNICAL REPORTS, PAPERS AND CONTRACTORS

A.1 NWMO Reports

- King, F. 2007. Overview of a carbon steel container corrosion model for a deep geological repository in sedimentary rock. Prepared by Integrity Corrosion Consulting Limited. Nuclear Waste Management Organization Report NWMO TR-2007-01. Toronto, Canada.
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A.4 Ph.D. Theses

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A.5 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

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Dr. G. Atkinson, Carlton University/ University of Western Ontario
Dr. J. Blatz, University of Manitoba
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FSS Canada Inc.
Dr. S. Frape, University of Waterloo
Gascoyne GeoProjects Inc.
Geological Survey of Canada
Geological Survey of Finland
Goodwin Environmental Assessment Consulting Inc.
G.R. Simmons & Associates Consulting Services Ltd.
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Dr. J. Sykes, University of Waterloo
Dr. R. Therrien, Université Laval
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APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2007

ABSTRACT

Title: Overview of a Carbon Steel Container Corrosion Model for a Deep Geological Repository in Sedimentary Rock
Report No.: NWMO TR-2007-01
Author(s): Fraser King
Company: Integrity Corrosion Consulting Limited
Date: March 2007

Abstract

A conceptual model for corrosion of a carbon steel (C-steel) used fuel container in a deep geological repository in sedimentary rock is described. The model takes into account various corrosion processes that might affect the container in the repository environment. Some processes, such as uniform corrosion and localized (pitting) attack, are specifically included in the conceptual model for the calculation of the used fuel container lifetime. Other processes, such as hydrogen-related effects, stress corrosion cracking, microbiologically influenced corrosion, preferential weld corrosion, and dry air oxidation are excluded from the conceptual model. This is based on the assumptions that either the environment will not support these processes or that these corrosion processes can be avoided by proper container design and fabrication procedures. The validity of these assumptions would still need to be demonstrated in the future through more-detailed engineering assessment, mathematical modelling, and experimental studies.

The extent of uniform corrosion should be assessed through a combination of (i) mass-balance arguments in the case of aerobic conditions, (ii) empirical corrosion rate data for the anaerobic phase, and (iii) a mechanistic mixed-potential model to provide support and justification for the calculations of the rate of wall loss. This combination of empirical calculations and mechanistic modelling provides a justifiable, robust prediction of the long-term uniform corrosion behaviour of a C-steel used fuel container.

Similarly, the effect of localized corrosion on the lifetime of C-steel containers should be assessed through a combination of empirical data and mechanistic modelling. Empirical data can be used to estimate the time-dependence of the degree of localization, whereas mechanistic modelling is used to justify these long-term predictions.

Preliminary C-steel corrosion assessments suggest that, based on a combination of uniform and pitting corrosion, the range of wall penetrations will be 9-34 mm after 10,000 years and 34-175 mm after 100,000 years. It is expected that a steel container would still have sufficient remaining wall thickness and mechanical strength to avoid container failure or through-wall penetration for a period of more than 10,000 years after it is placed in a repository in sedimentary rock. This analysis suggests, therefore, that C-steel containers can provide containment of used fuel for substantial periods of time in a deep geological repository in sedimentary rock.

ABSTRACT

Title: Seismic Activity in Northern Ontario portion of the Canadian Shield:
Annual Progress Report for the Period January 01 – December 31, 2006

Report No.: NWMO TR-2007-02

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: October 2007

Abstract

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC) continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2006.

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 2006.

During this twelve-month period 83 earthquakes were located. Their magnitude (m_N) ranged from 1.2 to 4.2. The largest of these events included a m_N 3.7, a m_N 3.4 and a m_N 4.2 in the Cochrane-Kapusksing region of Ontario. There was also a m_N 4.1 seismic event in the Sudbury region, but this has been associated with mining activity. The most westerly event in the area being studied was a m_N 2.2 event located near Kenora, ON. The 83 events located in 2006 compares with 103 events in 2005, 79 events in 2004, 45 located events in 2003 and 45 again in 2002. The general increase in located events is a reflection of the lower location threshold since the progressive addition of FedNor stations from 2003 to 2005.

ABSTRACT

Title: Used Fuel and Uranium Dioxide Dissolution Studies – A Review
Report No.: NWMO TR-2007-03
Author(s): D.W. Shoesmith
Company: The University of Western Ontario
Date: July 2007

Abstract

The extensive studies of used fuel dissolution inside a failed nuclear waste container have been reviewed. The primary factor controlling fuel dissolution is the redox condition established at the fuel surface by the radiolysis of water, how it evolves with time as radiation fields decay, and how it is influenced by the presence of oxidant scavengers, especially H_2 , produced by corrosion of the steel liner in the container.

If the container fails early, and oxidizing conditions are established, the fuel dissolution process will be a corrosion reaction driven by radiolytically-produced H_2O_2 . As radiation fields decay and conditions become less oxidizing, the fuel corrosion rate will decrease. The rate, and its evolution with time, will be influenced by the formation of corrosion product deposits, facilitated by calcium and silicate in the groundwater, which lead to the formation of insoluble U^{VI} phases. These deposits could partially block the fuel corrosion process, but could also lead to the formation of locally acidified sites at which the corrosion rate is increased. The location of these sites would be pores in the deposit and/or flaws in the fuel surface. If the groundwater contains sufficient bicarbonate, the formation of deposits would be inhibited and the fuel corrosion process possibly accelerated by the formation of bicarbonate-uranyl ion complexes.

As redox conditions become less oxidizing these issues become less important. The generation of acidity within deposits is unlikely, and since the corrosion rate becomes limited by the available concentration of oxidants, the influence of bicarbonate on the corrosion rate disappears. For sufficiently low radiation dose rates, a threshold for the transition from corrosion to chemical dissolution has been identified electrochemically and validated by dissolution rate measurements on used fuels and alpha-doped UO_2 specimens. For CANDU fuel this threshold is expected to occur between 10,000 and 20,000 years. Beyond this threshold fuel dissolution will be solubility-controlled and extremely slow.

The transition from radiolytic corrosion to chemical dissolution can be very rapidly induced in the presence of oxidant scavengers, especially H_2 . Small concentrations of H_2 suppress the redox condition to the threshold even for used fuels with high gamma/beta radiation fields. For sufficiently high concentrations, the establishment of the reversible H_2/H^+ reaction on noble metal epsilon particles can lead to galvanic protection of the fuel against corrosion. It is possible that this effect could lead to protection of the fuel against corrosion almost from the time of container failure. Under these conditions fuel dissolution and radionuclide release would be extremely small.

ABSTRACT

Title: Stress Corrosion Cracking of Copper in Nitrite/Chloride Mixtures at Elevated Temperatures
Report No.: NWMO TR-2007-04
Author(s): B. M. Ikeda¹ and C.D. Litke²
Company: ¹ University of Ontario Institute of Technology
² Atomic Energy of Canada Limited
Date: November 2007

Abstract

In this study, stress corrosion cracking (SCC) tests were carried out on oxygen-free phosphorous-doped copper specimens in nitrite-only solutions and in various nitrite/chloride mixtures at elevated temperatures of 100°C and 130°C, under both freely corroding and galvanostatic conditions. The results were compared with the results of previous SCC tests at room temperature of 22°C.

All copper specimens showed more ductile behaviour at 100°C. The stress corrosion factor (SCCF1) and surface crack extension rate (SCER) both suggested ductile or mixed SCC/ductile behaviour, but not pure SCC. The SCCF1 and SCER parameters were not sufficiently discriminating to distinguish between degrees of SCC and ductile tearing. Visual examination of the specimens was required to qualitatively estimate the amount of SCC for a copper specimen.

The results of experiments performed in nitrite-only solutions with a $1 \mu\text{A}\cdot\text{cm}^{-2}$ applied current (to simulate natural oxidation of copper) show that increasing the testing temperature from room temperature to 100°C decreases the extent of SCC and the surface-crack velocity. SCC was not observed for an applied current of $0.01 \mu\text{A}\cdot\text{cm}^{-2}$ suggesting that SCC susceptibility decreases with corrosion current.

In chloride-containing nitrite mixtures at elevated temperatures, all copper specimens tested displayed ductile cracking and no SCC. All chloride concentrations and nitrite/chloride concentration ratios tested inhibited the formation of SCC.

The experimental results show that SCC in nitrite and nitrite/chloride environments is suppressed at elevated testing temperatures. Therefore, the general SCC behaviour of copper in nitrite-only and nitrite/chloride environments at elevated temperatures may be conservatively assessed by performing appropriate SCC tests at room temperature.

ABSTRACT

Title: FRAC3DVS-OPG Enhancements: Subgridding, Hydromechanical Deformation and Anisotropic Molecular Diffusion
Report No.: NWMO TR-2007-05
Author(s): V. Guvanassen
Company: HydroGeoLogic, Inc.
Date: December 2007

Abstract

As part of the Nuclear Waste Management Organization's (NWMO) Technical Program, work program activities are being undertaken to further the understanding of groundwater flow system evolution and dynamics within crystalline and sedimentary rock settings. Numerical models applied as part of these activities must be able to effectively simulate flow and transport of radionuclides in deformable, fractured, porous media under variable density and non-isothermal conditions. The FRAC3DVS-OPG code has been used extensively within the NWMO's Technical Program. As part of the ongoing effort to further advance the application of FRAC3DVS-OPG as a flow and transport numerical code, a number of recent improvements have been made including:

- (i) coding and application of a previously developed sub-gridding technique;
- (ii) incorporation of an approach to better account for the effects of hydromechanical coupling; and
- (iii) incorporation of anisotropic molecular diffusion coefficient.

Hydromechanical coupling in the current version of FRAC3DVS-OPG is limited to the case of purely vertical strains with no lateral movements because hydromechanical coupling requires transient hydromechanical stresses as input for all elements within a given simulation domain. Approaches and recommendations to circumvent the above limitation are presented and discussed.

ABSTRACT

Title: Sub-Regional Modelling Case Study 2005-2006 Status Report
Report No.: NWMO TR-2007-07
Author(s): S.D. Normani, Y.-J. Park, J.F. Sykes and E.A. Sudicky
Company: University of Waterloo
Date: November 2007

Abstract

The Phase-II sub-regional model presented in this report is an improvement upon the Phase-I model developed in Sykes et al. (2004). Although the Phase-I sub-regional flow system case study provided valuable insight into the behaviour of flow domains characterized by complex, 3-dimensional, curve-planar fracture zones, a number of modelling scenarios relevant to a deep geologic repository and the impact of long-term climate change were considered a logical extension of the program. Boundary conditions, matrix and fracture zone parameters were modified and a statistical model of fracture zone permeability was developed, providing a depth varying probability density function (PDF).

Mean life expectancy (MLE) is shown to be an excellent tool for determining the most relevant and dominant geosphere parameters and processes that influence groundwater flow system characteristics in fractured, crystalline rock settings typical of the Canadian Shield. Mean life expectancy represents the average time for any subsurface location to discharge to the biosphere, while honouring both advective and diffusive dispersion processes (unlike particle tracking which can only honour advection). Since life expectancy is characterized by a probability density function, its mean may not represent earliest arrival or least dose, and hence, must be used with this caveat in mind.

The presence of brines at depth is shown to enhance the stability of deep groundwater flow systems since denser pore fluids at depth essentially reduce the topographic gradient (and driving forces) by requiring a greater energy potential to displace them. Mean life expectancy increases with increasing brine density at depth. It should be noted that the presence of brines at depth have a greater influence on the MLE of fluids in fractures than they do on fluids in the matrix.

MLE was used to assess the impact of fracture zone permeability, width, and porosity on travel time. The most significant of these is permeability, followed by width, and finally porosity. Decreasing fracture zone permeability can significantly increase MLE by several orders of magnitude at depth. The effects of fracture zone permeability assumptions on flow and transport are significant. Using a fracture zone permeability characteristic of near surface conditions at depth can significantly reduce the MLE, even in the adjacent matrix domain, especially if this higher permeability is used for fracture zones at depth.

For the cold-based (NN2008) and warm-based (NN2778) climate scenarios, sub-regional simulations illustrated that meltwater produced underneath the ice sheet is able to penetrate deeper in the warm-based scenario. This is primarily due to the absence of permafrost, which in the case of NN2008, acts to seal the near surface and greatly reduces, by several orders of magnitude, the hydraulic connection with the fracture zone network.

ABSTRACT

Title: Status of the Understanding of Used Fuel Container Corrosion Processes – Summary of Current Knowledge and Gap Analysis
Report No.: NWMO TR-2007-09
Author(s): Fraser King
Company: Integrity Corrosion Consulting Limited
Date: October 2007

Abstract

This report is a summary of the status of the knowledge of the corrosion behaviour of copper and carbon-steel used-fuel containers, and the gaps in this knowledge.

A brief review of the current level of understanding of used-fuel container corrosion is given. This review draws on information developed as part of the Canadian research and development program for long-term management of Canada's used nuclear fuel and from similar international programs that are also considering the use of copper or carbon-steel containers in their deep geological repository concepts.

Within the Canadian research program, the understanding of the corrosion behaviour of copper is relatively mature, having been the subject of detailed studies over the past 20 years. However, there are still some areas of uncertainty or areas that require additional effort, including corrosion under unsaturated conditions, the potential for microbiologically influenced corrosion, the evolution of corrosion damage from the initial warm, aerobic phase to the long-term cool, anaerobic period, and stress corrosion cracking.

The carbon-steel corrosion research program is much less mature within the Canadian context, although there is considerable experience within the Japanese and various European programs. Much of the existing information is transferable to conditions expected within a Canadian deep geological repository, but there are areas requiring further study, including: corrosion under unsaturated conditions, the evolution of corrosion damage, microbiologically influenced corrosion, stress corrosion cracking, and hydrogen gas generation.

Gaps in the existing knowledge have been identified in these and other research areas. These gaps have been grouped into proposed research areas or programs for future consideration.

ABSTRACT

Title: Potential Implications of Microbes and Salinity on the Design of Repository Sealing System Components

Report No.: NWMO TR-2007-10

Author(s): S. Stroes-Gascoyne¹ P. Maak², C.J. Hamon¹ and C. Kohle¹

Company: ¹Atomic Energy of Canada Limited and ²Nuclear Waste Management Organization

Date: November 2007

Abstract

A study was undertaken to evaluate the potential impacts of microbial activity and salinity on the design of repository sealing system components, with an emphasis on the design of the bentonite buffer which would surround a used-fuel container in a deep geological repository. Laboratory experiments were conducted to study the effects of an in situ decrease in dry density in compacted MX-80 bentonite (from a starting dry density of 1.6 g/cm³ to about 1.0 g/cm³) on the aerobic microbial culturability, and hence microbial activity, in compacted bentonite under both low-salinity (distilled deionized water) and high-salinity (NaCl 100 g/L) conditions. The experiments were designed to simulate the effects of a bentonite-container placement gap in the design of a deep geological repository for used nuclear fuel under various conditions.

The present experimental results suggest that in a low-salinity environment, a high bentonite dry density of 1.6 g/cm³ and the associated high swelling pressure are required in the design of a deep geological repository to suppress the microbial activity in compacted bentonite buffer surrounding the used-fuel containers. Therefore, in a low-salinity environment, it would be important to ensure that the design of bentonite dry density will be at or above the desirable as-placed density of 1.6 g/cm³, both during the transient period of the resaturation process and at times when all sealing system components are equilibrated. The ability to achieve such a high as-placed bentonite dry density at all locations in the vicinity of used-fuel containers in a deep geological repository would be an important factor in the selection of a container placement method and repository design.

The present experimental results also suggest that in a high-salinity repository environment, salinity at or in excess of 100g/L will suppress the activity of indigenous microorganisms in the as-purchased MX-80 bentonite at or near the container surface. This appears to occur in bentonite with an as-placed dry density as low as about 1 g/cm³. With salinity as the dominant factor for controlling microbial activity, the ability to achieve high as-placed dry bentonite densities would not be considered as an important factor for selecting a container placement method and hence repository design, in a high-salinity repository environment.

These experimental results are applicable for microbial activity indigenous to the as-purchased MX-80 bentonite. If saline-tolerant (halotolerant or halophilic) microorganisms were present or introduced into a deep geological repository, high as-placed dry bentonite densities may be required to suppress microbial activity.

ABSTRACT

Title: Evaluation of Experimental Protocols for Characterizing Diffusion in Sedimentary Rocks
Report No.: NWMO TR-2007-11
Author(s): P. Vilks and N.H. Miller
Company: Atomic Energy of Canada Limited
Date: December 2007

Abstract

Laboratory protocols have been developed, and preliminary testing has been undertaken to estimate the porosity, pore size, effective diffusion coefficients, pore water composition and permeability using archived core samples from Ordovician-aged shale and limestone formations from southern Ontario. Porosity was estimated by a water immersion technique and pore size distribution was determined using mercury intrusion porosimetry. Through-diffusion cell experiments were used to estimate effective diffusion coefficients, as well as rock capacities and effective tortuosities which provide a measure of pore geometry. Sample permeability was estimated with the High Pressure Radionuclide Migration Apparatus by pumping water through core samples under a confining pressure. In addition, thirty-day leaching experiments with deionized water were used to extract salts in accessible pore spaces for use in estimating pore fluid compositions based on sample porosity.

Archived core samples of Queenston shale and Cobourg (Lindsay) limestone were used to test the experimental protocols, and to perform a preliminary assessment of mass transport properties of these formations. The Queenston shale was found to have an average porosity of 0.066 ± 0.005 , and average iodide and tritium diffusion coefficients of $(1.2 \pm 0.3) \times 10^{-12}$ and $(1.1 \pm 0.3) \times 10^{-11}$ (m^2/s). The Cobourg limestone had an average porosity of 0.017 ± 0.003 , and average iodide and tritium diffusion coefficients of $(1.2 \pm 2.4) \times 10^{-12}$ and $(3.9 \pm 4.8) \times 10^{-12}$ (m^2/s). The average pore diameters of shale and limestone were 6.2 ± 0.9 nm and 7.7 ± 1.6 nm, respectively. The matrix permeability of these samples was very low, with average values of $(4.5 \pm 5) \times 10^{-21}$ (m^2) for Queenston shale and $(9.4 \pm 7.0) \times 10^{-22}$ (m^2) for Cobourg limestone. Porosity and pore geometry variation accounted for differences in diffusivity and permeability between shale and limestone. Leaching experiments to extract soluble salts indicated that the pore waters in Ordovician sediments are highly saline, with Total Dissolved Solid (TDS) values estimated to range from 180 to 270 g/L. These compositions are consistent with the compositions of groundwaters from wells within Ordovician-aged formations in southern Ontario.

ABSTRACT

Title: Reactive Transport Modelling in Sedimentary Rock: State-of-Science Review
Report No.: NWMO TR-2007-12
Author(s): K. U. Mayer¹ and K. T. B. MacQuarrie²
Company: ¹University of British Columbia, ²University of New Brunswick
Date: December 2007

Abstract

To assess the suitability of sedimentary rock units for hosting deep geological repositories (DGR) for used nuclear fuel, it is necessary to investigate the long term geochemical stability of these formations. Multicomponent reactive transport modelling provides a viable method to evaluate conceptual models and to assess parameter sensitivity in the context of rock-water interaction, and can thus support and complement expensive field investigations. In this report, hydrogeological and hydrogeochemical data are reviewed to identify the relevant transport and reaction processes that control groundwater evolution and composition. In addition, previous reactive transport modelling efforts in similar settings are reviewed to assess the current status of reactive transport modelling in sedimentary rock formations. Based on this information, model capabilities and formulation gaps are identified. In addition, recommendations are made on how reactive transport modelling could be used most effectively to evaluate redox stability and salinity evolution in sedimentary rock units in response to periods of glaciation and deglaciation. It is found that reactive transport modelling has not been previously used to assess such a scenario. However, modelling studies of seawater ingress and CO₂ sequestration in sedimentary rocks show promising results and suggest that modelling of the geochemical evolution in a 2D-subsection of a sedimentary basin is a realistic goal. Although there are advanced multicomponent reactive transport models that consider a wide range of the required processes including aqueous speciation, ion exchange, mineral dissolution-precipitation, microbially-mediated redox reactions, density coupling between flow and reactive transport, as well as porosity and permeability changes, none of the currently available codes is capable of capturing all processes of relevance. The MIN3P code belongs to this group of codes and it is recommended that the capabilities of this model be expanded to include a) the Pitzer ion interaction model, b) a modified formulation for microbially-mediated reactions that accounts for inhibition as a function of salinity, c) a formulation for multicomponent and species-dependent diffusion, and d) discretization methods that facilitate the generation of unstructured grids that are better capable of dealing with irregular geometry and outcropping aquifer and aquitard units. Furthermore, it is recommended that the enhanced code be used to investigate a series of conceptual models for sedimentary units; within the context of these models, the effect of parameter uncertainty can be evaluated with respect to recharge penetration depth, redox stability and salinity evolution.

ABSTRACT

Title: EBS Task-Force Modelling Report: Modelling AECL's Tests - Isothermal Test and Buffer/Container Experiment
Report No.: NWMO TR-2007-13
Author(s): R. Guo
Company: Atomic Energy of Canada Limited
Date: December 2007

Abstract

In order to investigate how heat affects the performance of a dense bentonite-sand buffer, two full-scale in-situ experiments, the Isothermal Test (ITT) and the Buffer/Container Experiment, were conducted by Atomic Energy of Canada Limited (AECL). In the Buffer/Container Experiment, there was a full-size electric heater simulating the heat output of a disposal container of used fuel installed vertically in a 1.24-m-diameter by 5-m-deep borehole surrounded by a clay-based buffer. The borehole was drilled in the floor of a room excavated in Canadian Shield granite on the 240 Level of AECL's Underground Research Laboratory (URL). The thermal, hydraulic and mechanical response was monitored in the buffer and in the surrounding rock. Power was provided to the heater for approximately 896 days. The Isothermal Test was installed in an identical borehole also drilled in Canadian Shield granite on the 240 Level of AECL's URL to investigate the hydraulic interaction between the buffer and rock without influence of thermal gradient. The bottom two metres of the Isothermal Test borehole was filled with an in situ compacted buffer material. This material was capped by a 1.25-m-thick plug of high-performance concrete and was monitored for 6.5 years.

The Nuclear Waste Management Organization (NWMO) sponsors AECL's participation in the Engineering Barrier System Task Force (EBS TF) modelling group. The information about ITT and the Buffer/Container Experiment is shared by the EBS TF numerical modelling group for use in evaluating the effectiveness of several mathematical models in predicting the evolution of the coupled processes in unsaturated clay-based material. This report is part of NWMO's AECL's input of modelling results to the EBS TF.

Numerical simulations were conducted using CODE_BRIGHT to model the evolution of the pore pressure in the unsaturated bentonite-sand buffer and the surrounding rock as well as mechanical response of the buffer during the 6.5 years of water uptake for the ITT and the evolution of the temperature, thermally induced pore water pressure and mechanical response in the buffer and the surrounding rock for the Buffer/Container Experiment.

The influence of the excavation-induced damage zone on the evolution of the hydraulic response in the bentonite-sand material and the rock was examined. The simulated water seepage from the rock to the borehole was compared with measured results for both the ITT and the Buffer/Container Experiment. The simulated pore water pressure in the rock and the pore water suction in the buffer were compared with data measured during the test and inferred from end-of-test buffer moisture conditions for both the ITT and the Buffer/Container Experiment. The modelled vertical displacements in the rock are also compared with the measured data in the Buffer/Container Experiment. Based on the comparison of the simulated thermally induced pore water pressure in the rock with measured pore pressure, the possible range of rock permeability, and its dependence on temperature, is discussed. The simulated displacements in the buffer and the stresses in the rock are also presented in this report.

ABSTRACT

Title: Numerical Modelling of a Deep Geological Repository Using the In-Floor Borehole Placement Method
Report No.: NWMO TR-2007-14
Author(s): R. Guo
Company: Atomic Energy of Canada Limited
Date: December 2007

Abstract

A series of three-dimensional finite element, thermal transient and thermal-mechanical stress analyses is performed to gain a better understanding of the behaviour of the plutonic rock mass in the near-field and far-field of a deep geological repository using an in-floor borehole placement method. For these analyses, the repository is conservatively assumed to be located at 1,000-m depth in granitic rock with characteristics similar to the sparsely fractured, highly stressed rock of the Whiteshell Research Area near Pinawa and Lac du Bonnet, Manitoba.

Three-dimensional near-field modelling using the thermal load corresponding to the gross thermal load and a far-field modelling using the dimensions of the in-room placement method are conducted using CODE_BRIGHT. The near-field and far field modelling results obtained in the present study appear to match reasonably well with those results from a previous modelling exercise performed using ABAQUS. Both results indicate that thermally acceptable repository layouts can be achieved using the in-floor borehole placement method.

Far-field thermal analyses are conducted for a repository with finite dimensions and for a repository with infinite horizontal dimensions, and the temperature results in the region of the placement room and borehole are compared. The differences in temperature between the far-field analyses are used to correct the temperatures from the near-field analyses, which simulate a repository with infinite horizontal dimensions. The temperature correction becomes significant about 1,000 years after container placement. Therefore, the results from near-field modelling using the boundary conditions for an infinite repository model can be used to represent the results for a finite repository for times less than 1,000 years.

Mechanical responses and stability of the rock around the placement room and the in-floor borehole are analysed by performing coupled thermal-mechanical near-field modelling. For the assumed depth, in situ stress and rock strength characteristics, and borehole diameter and spacing, the results imply that:

- excavation of the placement room will not cause failure in the rock, and
- drilling of the in-floor borehole may cause breakout and a zone of excavation damage near the in-floor borehole wall and in the rock on the placement room floor between adjacent boreholes.

Future conceptual designs for a deep geological repository using the in-floor borehole placement method will need to consider the physical and chemical characteristics of any proposed sites for long-term used fuel management.

ABSTRACT

Title: POLARIS Underground Project at SNO (P.U.P.S.)
Report on Year 1 Studies
Report No.: NWMO TR-2007-16
Author(s): Gail Atkinson and SanLinn Kaka
Company: Carleton University
Date: December 2007

Abstract

This report describes Year 1 studies of the PUPS (POLARIS Underground Project at Sudbury Neutrino Observatory) project. The main objective of PUPS is to conduct an experiment in 3-dimensional seismic monitoring at Sudbury Neutrino Observatory (SNO) to address a range of scientific or engineering objectives related to underground tunnel operations. In the first year, useable signals from about 15 local and regional events were recorded and analyzed, including near-source signals from the MN 4.1 Lively earthquake. The influence of near-surface site effects for rock sites and the potential effects of seismic response due to the free surface in cavities and tunnels was studied. Comparisons of the signals measured on the surface to those at subsurface locations were carried out to address these effects. A number of important ground-motion parameters, such as the high-frequency decay parameter, κ , and earthquake stress drop, were also evaluated for local and regional events.

A key conclusion is that underground motions appear to be lower than those at the surface, but there is much inter-event variability, and a larger number of recordings is required to firmly establish mean trends. The ratio of horizontal to vertical component motions on the surface is larger than that underground. For underground sites, horizontal and vertical component amplitudes are similar. There is significant high-frequency decay of ground motions from nearby events at both surface and underground sites, suggesting an important source-related high-frequency decay (“ κ ”) effect. Stress drops from small local earthquakes, of magnitude 1.4 to 2.8, are generally low (<50 bars). These factors (κ and low stress) may act to limit high-frequency ground motions.

Further monitoring and analysis is recommended to better define the trends noted in the 1st year of study. Additional areas of investigation are also proposed to take advantage of the unique geometry of this experiment.

ABSTRACT

Title: GEOLOGY OF THE CANADIAN SHIELD IN ONTARIO: AN UPDATE
Report Number: 06819-REP-01200-10158-R00
Author(s): J.A. Percival¹, R.M. Easton²
Company: ¹ Geological Survey of Canada
² Precambrian Geoscience Section, Ontario Geological Survey
Date: June 2007

Abstract

The report reviews advances in understanding the geology of the Canadian Shield in Ontario since the 1992 compilation provided in the Ontario Geological Survey *Geology of Ontario* special volume. New information includes data and interpretations produced during several recent major initiatives: Operation Treasure Hunt, Discover Abitibi, the Abitibi–Grenville and Western Superior Lithoprobe transects, Western Superior National Mapping Program (NATMAP) transect, and many updated maps and data sets. In addition to a descriptive overview, the report contains a set of digital geology and geophysical maps, along with distribution of point data from published databases of geochronology, litho geochemistry, drill hole locations, and earthquake location-magnitude.

Two main geological provinces of the Canadian Shield are represented in Ontario. The Superior Province and autochthonous cover sequences underlie approximately 80 percent of the province of Ontario, distributed mainly across the north and northwest. The Grenville Province, exposed in the southeast, and its autochthonous cover, make up the remainder.

The Superior Province records about one billion years of geological history, from 3.6 to 2.6 billion years ago. Five microcontinental fragments evolved independently between 3.6 and 2.75 Ga, prior to a series of five discrete accretionary events between 2.72 and 2.68 Ga that assembled the continental and intervening oceanic crustal domains into a coherent Superior craton. The Northern Superior superterrane recorded 3.6 to 2.75 Ga events prior to 2.72 Ga collision with the 3.0 Ga North Caribou superterrane. Following rifting at 2.98 Ga, the Uchi margin of the North Caribou superterrane evolved in an upper-plate setting before collision 2.72 to 2.70 billion years ago of the Winnipeg River terrane (<3.4 Ga), which trapped synorogenic English River turbidites in the collision zone. The Winnipeg River terrane was reworked in magmatic and tectonic events 2.75 to 2.68 billion years ago, including the central Superior orogeny (2.71-2.70 Ga) that marks accretion of the juvenile western Wabigoon terrane. In the south, the Wawa–Abitibi terrane evolved in a mainly oceanic setting until Shebandowanian collision with the composite Superior superterrane at 2.695 Ga. Synorogenic Quetico turbidites were trapped in the collision zone. The final accretionary event involved addition of the Minnesota River Valley Terrane (MRVT) from the south, and deposition and metamorphism of synorogenic turbidites of the Pontiac terrane during the Minnesotan orogeny (ca. 2.68 Ga). Seismic reflection and refraction images indicate north-dipping structures, interpreted as a stack of discrete, 10 to 15 km thick terranes. A slab of high-velocity material, possibly representing subcreted oceanic lithosphere, as well as Moho offsets, support a model of progressive accretion through plate-tectonic-like processes. Following stabilization in the Neoproterozoic, the craton was affected by emplacement of at least 11 dyke swarms (2.45-1.1 Ga), uplift of the Kapuskasing zone (ca. 1.9 Ga), ductile reworking of the northwestern margin (ca. 1.8 Ga), and attempted rifting (ca. 1.1 Ga). Minor seismicity occurs in the Lake Timiskaming seismic zone.

The Grenville Province contains rocks ranging in age from 2.69 to 0.99 Ga, metamorphosed between 1.08 and 0.99 Ga. It is bounded to the northwest by the subvertical Grenville Front. Within the Grenville Province, there is an overall, generally shallow (20-40°), southeasterly dip to both surface geological structures and seismic reflectivity within the crust, suggesting northward thrusting of deep-level crustal rocks. Abitibi–Grenville LITHOPROBE seismic data suggests that the Superior Province continues at least 200 km southeast of the Grenville Front as a southward-tapering wedge in the Grenville lower crust.

Tectonic stability has prevailed since *circa* 1.0 Ga in most of the Grenville Province, when it is thought that a mountain range and plateau existed, similar to the modern-day Himalayas and the Tibetan plateau. The mountains were peneplained by the time of deposition of Paleozoic limestones at *circa* 0.42 Ga. Neoproterozoic and younger tectonic activity is limited to localized rifting at *circa* 0.59 Ga along the Ottawa graben and along an east-trending corridor along the Mattawa, French and Pickerel rivers, and Lake Nipissing. In addition, subsequent rifting during the Jurassic, at *circa* 0.17 Ga, resulted in the formation of the Ottawa–Bonnechere graben system, as well as the localized injection of lamprophyric and kimberlitic dikes in the eastern Grenville Province in Ontario. In addition, emplacement of several mafic dyke swarms occurred prior to, during, and after the Grenville Orogeny. It has been suggested that significant neotectonic activity persists in the “Golden Horseshoe” area and along the north shore of Lake Ontario and the St. Lawrence River. At present, apart from localized, low-level seismicity in the “Golden Horseshoe” area near the subsurface trace of the Central Metasedimentary Belt boundary zone, there is no compelling evidence that significant neotectonic activity, has, or is, occurring in the Grenville Province.

ABSTRACT

Title: TECHNICAL RESEARCH AND DEVELOPMENT PROGRAM FOR LONG-TERM MANAGEMENT OF CANADA'S USED NUCLEAR FUEL – ANNUAL REPORT 2006

Report Number: 06819-REP-01200-10163-R00

Author(s): S. Russell, F. Garisto, P. Gierszewski, M. Hobbs, M. Jensen, T. Kempe, T. Lam, P. Maak, G. Simmons¹, A. Vorauer and K. Wei

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Date: March 2007

Abstract

This report is a summary of progress in 2006 for the technical research and development program for long-term management of Canada's used nuclear fuel.

Significant achievements in 2006 include:

- As part of an effort to maintain technical capability and to ensure broad input to the research program, the work has diversified over the past few years to include participation of 11 Canadian universities.
- Canada participated in several projects at the SKB Äspö Hard Rock Laboratory in Sweden, including the LASGIT Gas Injection Test, the LTDE In-situ Diffusion and Colloid Dipole Projects, the Groundwater Modelling Task Force, and the Engineered Barrier Task Force, the Canister Retrieval Test, Tunnel Backfilling project and the Rock Shear Experiment.
- A Workshop entitled “Future Direction for the Repository Development Program” was organized and held in Winnipeg, Manitoba. The Workshop was attended by over twenty technical program staff and consultants with both Canadian and international experience in the development of deep geological repository concepts in various host rock media.
- A framework was developed for long-term monitoring of a deep geological repository for used nuclear fuel. The framework identifies monitoring program objectives and suggests possible approaches. The results illustrate how a suitable monitoring program could be developed, and identified some specific issues that should be addressed prior to implementation.
- The influence of hydrogen on the corrosion potential of SIMFUEL (unirradiated natural uranium dioxide fuel modified (doped) to replicate the chemical composition of used nuclear fuel) was found to be more pronounced as the doping level of the SIMFUEL increases, i.e., hydrogen would be more effective at preventing corrosion of higher burnup uranium fuels. For the highest doping level, the corrosion potential approaches -400mV, the potential below which fuel oxidation does not occur.
- An analytic protocol was developed that allows the measurement of stable iodine in natural samples using standard equipment at levels much less than previously available. This technique will make it easier to obtain biosphere data for iodine-129, a key radionuclide for postclosure safety assessment.
- A numerical case study was performed to quantify the importance of several scenarios associated with the long-term monitoring and closure of a deep geological repository using a representative hypothetical site on the Canadian Shield. For example, monitoring at the

tunnel end of placement boreholes may be useful in providing evidence for lack of container failure since there is a natural gradient towards the open tunnels near the deposition rooms during the extended monitoring period.

- Canada was represented by Atomic Energy of Canada Limited (AECL) on SKB's Engineering Barrier Systems Task Force (EBS-TF). AECL completed coupled thermal-hydraulic-mechanical analyses of a laboratory-scale heating test used as a 2006 modelling benchmark. The EBS-TF has invited NWMO to submit additional modelling benchmark case studies in 2007 based on AECL's Isothermal Test and Buffer Container Experiment.
- Microbial measurements were completed in samples of bentonite sealing material from in-situ field experiments and a series of laboratory tests, covering a range of density and salinity. The results identify the conditions (e.g., water activity, salinity and density) that are required to minimize the viability of microbes in bentonite.
- A collaborative review with the Geological Survey of Canada and the Ontario Geologic Survey (OGS) has updated and advanced the understanding the geology of the Canadian Shield in Ontario since the 1992 compilation provided in the OGS *Geology of Ontario* special volume. New information includes data and interpretations produced during several recent major initiatives: Operation Treasure Hunt, Discover Abitibi, the Abitibi–Grenville and Western Superior Lithoprobe transects, Western Superior NATMAP transect, and many updated maps and data sets.
- The influence of long-term climate change and glaciation on the Canadian landscape continued to be explored with the University of Toronto Glacial Simulation Model. Key activities in 2006 included the completion of reports establishing the nature of transient surface boundary conditions during the last Laurentide glacial cycle and an assessment of sub-glacial hydrology that potentially could influence the stability and evolution of deep seated groundwater flow system in a Canadian Shield terrain.
- Regional simulations of groundwater flow in fractured crystalline shield settings by the University of Waterloo have demonstrated the effectiveness of the groundwater flow and transport code FRAC3DVS which honours the physics of advection, diffusion and mechanical dispersion in identifying governing geosphere parameters. Variably saline groundwater chemistries are demonstrated to enhance the safety of a deep geological repository by retarding the migration of contaminants released in the deep-seated brine region and delaying groundwater discharge to the surface.
- A numerical modelling team from Laval University continued to participate on the international Äspö Task Force (ATF) on Groundwater Flow and Transport. As part of Task 7 activities, FRAC3DVS has been applied to simulate and demonstrate a methodology for the interpretation of a large scale hydraulic interference pump test conducted by POSIVA at its fractured crystalline rock Olkiluoto site in Finland.
- As part of Canada's contribution to the Äspö Colloid Project field scale tests, AECL completed a complementary series of laboratory scale transport experiments using bentonite and latex colloid tracers in a 1 m² quarried block fracture. The results of this experimental program provide unique insight into the complex nature and stability of colloid migration within a single variable aperture fracture under varied geochemical conditions.