Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2011

NWMO TR-2012-01

April 2012

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Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION

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ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2011**
Report No.: **NWMO TR-2012-01**
Author(s): L. Kennell, K. Birch, R. Crowe, D. Doyle, J. Freire-Canosa, M. Garamszeghy, F. Garisto, M. Gobien, S. Hirschorn, N. Hunt, P. Keech, E. Kremer, T. Lam, H. Leung, J. McKelvie, C. Medri, A. Murchison, A. Parmenter, U. Stahmer, E. Sykes, J. Villagran, A. Vorauer, T. Wanne and T. Yang
Company: Nuclear Waste Management Organization
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Abstract
This report is a summary of activities and progress in 2011 for the Nuclear Waste Management Organization's (NWMO's) Technical Program. The primary purpose of the Technical Program is to support the implementation of Adaptive Phased Management (APM), Canada's approach for long-term management of used nuclear fuel. Significant technical program achievements in 2011 include:

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

- NWMO provided research contracts and research grants to 14 Canadian universities and supported 6 postgraduate scholarships in 2011 as an approved industrial partner with the Natural Science and Engineering Research Council of Canada.

- NWMO's research program published 18 NWMO technical reports, 6 peer-reviewed journal articles, and submitted 21 abstracts for presentation at international conferences focused on environmental radioactivity and radioactive waste management.

- A program was initiated in 2011 to assess the use of copper coating technologies as a method to build a corrosion barrier on a steel container surface. Several technologies including cold spray, laser clad overlay and electrodeposition are being investigated. Researchers from the University of Windsor, University of Ottawa, McGill University, University of Western Ontario, and the National Research Council of Canada, are involved in the project.

- NWMO conducted research on used fuel container corrosion, repository sealing material development and repository design. NWMO also continued to develop a repository monitoring and retrieval program, and continued to review developments in used fuel reprocessing and alternative waste management technologies. Two technical reports on copper corrosion were published in 2011. The first report discusses the state of knowledge on copper corrosion under conditions representative of groundwaters in crystalline rock environments and includes a status report on Stress Corrosion Cracking (SCC). The second report reviews the results of corrosion studies during the past twenty years for copper used fuel containers in low salinity groundwater.

- NWMO continued to refine engineering conceptual designs, cost estimates, transportation logistics and implementation schedules in support of APM. The design of Used Fuel Packing Plant systems was advanced as well. A conceptual design for a used fuel transfer line was developed. Further development and demonstration of this fuel bundle transfer system design is planned for the period 2012-2018.

- The NWMO geoscience program continued to develop plans and methods for detailed site investigations in both crystalline and sedimentary rock in the fields of: geology, hydrogeochemistry, radionuclide transport, microbiology, geomechanics, seismicity, petrophysics and hydrogeology. NWMO continued to develop numerical modelling methods that can be used to assess long-term geosphere stability associated with natural perturbations (e.g., glaciation, seismicity) and deep groundwater system dynamics.

- NWMO continued to maintain and improve the models and datasets used to support the safety assessment requirements of potential sites and repository designs.

- NWMO initiated work on the Fourth Case Study, a postclosure safety assessment of an APM deep geological repository in crystalline rock using the reference design for a facility at a hypothetical site.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM) for long-term management of used nuclear fuel, the approach recommended in *"Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel"* (NWMO, 2005) and selected by the Government of Canada in June 2007. The APM Technical Program is focused on developing preliminary designs, cost estimates, associated research activities and safety cases for a used fuel deep geological repository in order to ensure continuous improvement and consistency with international best practice. Examples of conceptual designs for a deep geological repository are illustrated in Figure 1.1 and Figure 1.2.

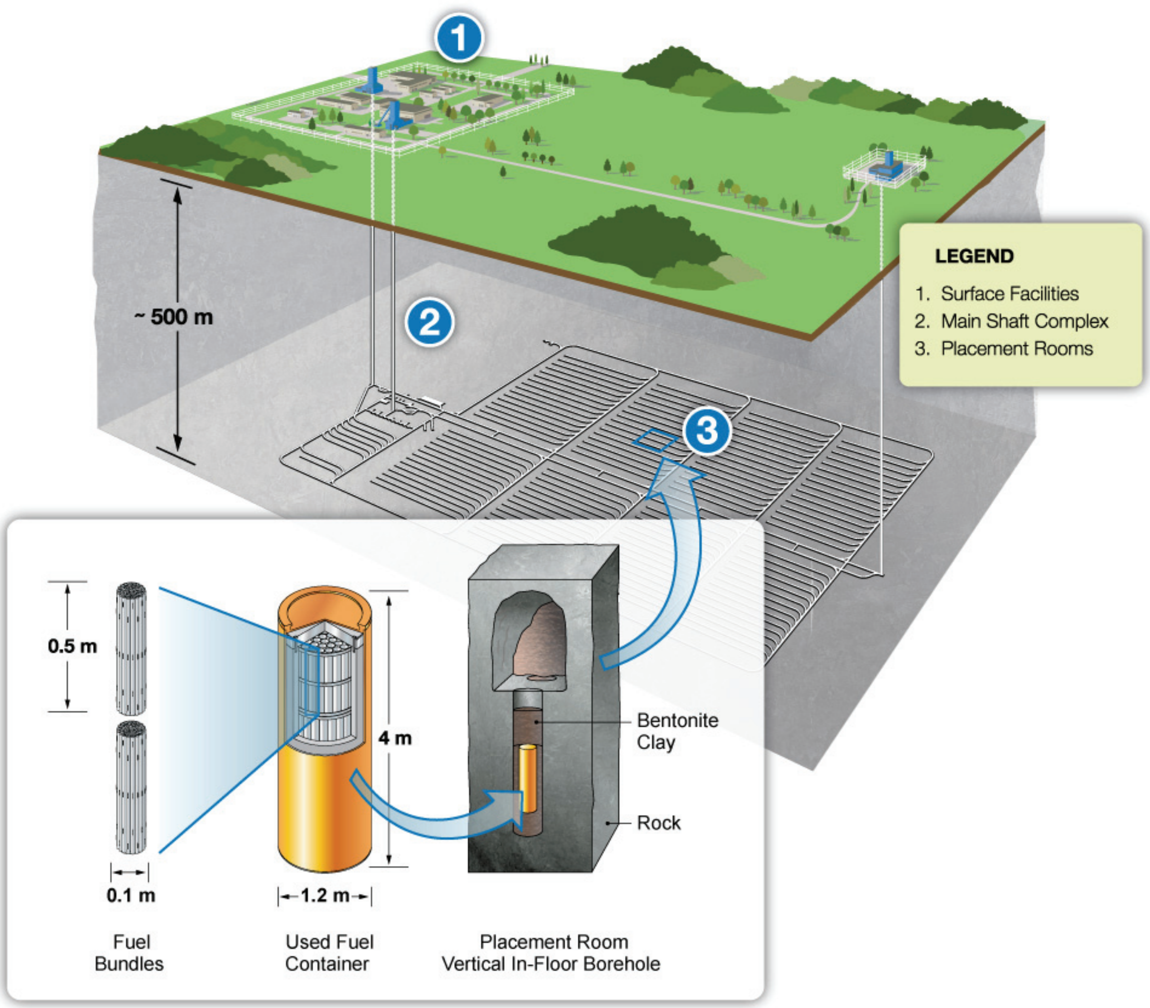

Figure 1.1: Illustration of a Deep Geological Repository – In-floor Borehole Placement

In 2011, the NWMO continued to implement the site selection process for a deep geological repository for Canada's used nuclear fuel. The suitability of potential candidate sites to safely host a DGR is being evaluated against site selection criteria defined in "*Moving Forward*

Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel" (NWMO, 2010). The steps for evaluating the geological suitability of willing and informed host communities consist of: a) initial screenings to evaluate the suitability of candidate sites against a list of initial screening criteria, using readily available information; b) feasibility studies to further determine if candidate sites may be suitable for developing a safe used fuel repository; and, finally, c) detailed field investigations to confirm suitability of one or more sites based on detailed site evaluation criteria. Each step is designed to evaluate the site in greater detail than the previous step.

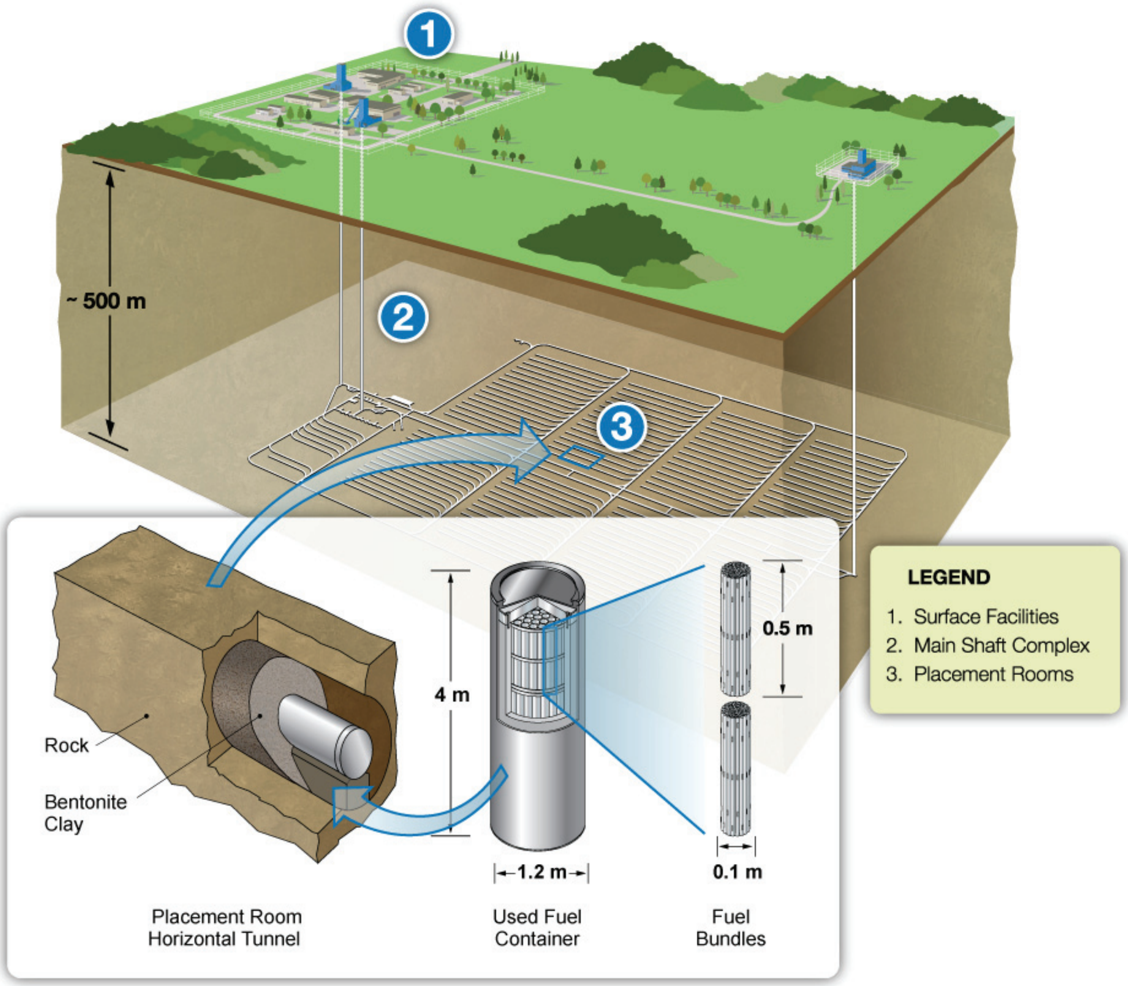

Figure 1.2: Illustration of a Deep Geological Repository – Horizontal Tunnel Placement

NWMO completed initial screenings for nine communities in 2011, and will continue to conduct initial screenings in 2012. The initial screening reports are published on NWMO's site selection website (http://www.nwmo.ca/sitingprocess). In 2012, the NWMO will initiate feasibility studies for those communities that have decided to move onto this next step in the site selection process.

The following chapters summarize the various work programs and progress for the APM Technical Program in 2011.

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 REGULATORY FRAMEWORK

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

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

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

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

The application for a CNSC licence for a used nuclear fuel DGR would trigger an Environmental Assessment (EA) under the *Canadian Environmental Assessment Act (CEAA)*. Under the CEAA, an EA is required to assess the environmental effects of most projects requiring federal action or decision. Public input will be required at appropriate stages in the EA and licensing process.

For the pre-project phase of APM, the CNSC established a special project arrangement with the NWMO in March 2009, which includes CNSC review of NWMO information on conceptual APM design to identify any regulatory concerns. The CNSC has agreed to review APM conceptual designs and illustrative safety assessments in representative host rock formations (one in crystalline rock and one in sedimentary rock).

2.2 APM TECHNICAL PROGRAM OBJECTIVES & OVERVIEW

The primary objective of the APM Technical Program is to complete the preliminary designs, safety cases, cost estimates and generic research activities for a used fuel deep geological repository to support a licence application following planned selection of a preferred site in a 2018 timeframe.

To support the primary objective of the APM Technical Program, the following Technical Program objectives have been developed:

- Prepare updated generic reference designs, cost estimates and safety cases for a deep geological repository.
- Obtain Canadian Nuclear Safety Commission pre-project review of reference designs and safety cases for a deep geological repository by 2013.
- Develop and demonstrate the full range of components for transferring used fuel from reactor site storage into a DGR by 2018.
- Further increase confidence in the DGR safety case.
- Enhance scientific understanding of processes that may influence repository safety.
- Maintain awareness of advances in technology development and alternative methods for long-term management of used nuclear fuel.
- Evaluate the adequacy of potential candidate sites for a deep geological repository by conducting site characterizations and safety evaluations.

The four main work areas supporting these objectives are:

1. Preparing conceptual designs, costs and safety cases (objectives 1 and 2);
2. Developing a used fuel transfer system (objective 3);
3. Building confidence in the safety case (objectives 4, 5 and 6); and
4. Conducting geoscientific site characterization and evaluation (objective 7).

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

A list of the technical reports produced by NWMO in 2011 is provided in Appendix A.1. Their respective abstracts are provided in Appendix B. All technical reports published before 2000 are listed in Garisto (2000), while the 2000 to 2010 reports are listed in corresponding annual progress reports (Gierszewski et al., 2001, 2002, 2003, 2004a; Hobbs et al., 2005, 2006; Russell et al., 2007; Birch et al., 2008, Kremer et al., 2009, McKelvie et al., 2010, 2011).

Appendix A.2 provides a list of the publications and presentations made by APM Technical Program staff and contractors. Appendix A.3 provides a list of graduate students awarded industrial postgraduate scholarships. Appendix A.4 provides a list of the primary external contractors and collaborators for the technical work program.

2.3 SUMMARY OF INTERNATIONAL ACTIVITIES

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

Since 2004, Canada has been participating in experiments associated with the SKB Äspö Hard Rock Laboratory (HRL). The purpose of this participation is to improve our understanding of key processes in a repository in crystalline rock through involvement in large-scale projects. NWMO's involvement facilitates collaboration and sharing of lessons learned in repository technology development and site characterization. In 2011, NWMO continued to participate in the following work programs at the Äspö HRL:

- Bentonite Colloid Transport Project;
- LASGIT Gas Injection Test (LArge Scale Gas Injection Test);
- Engineered Barrier System Modelling Task Force; and
- Groundwater Modelling Task Force.

NWMO is a partner in the Mont Terri Project, which involves of a series of experiments carried out in the Mont Terri rock laboratory in Switzerland. The main aims of the project are: to test and improve techniques for hydrogeological, geochemical and geotechnical investigations in an argillaceous formation; to characterize the Opalinus Clay and its behaviour; to explore the interactions between the Opalinus Clay and other materials (such as engineered barriers); and to carry out research relevant to repository implementation (e.g., demonstration experiments). The experiments being conducted at Mont Terri have relevance for NWMO site characterization, engineering and safety assessment activities. Involvement in the Mont Terri Project allows NWMO to participate in state-of-science research in collaboration with 14 international project partners, including several waste management agencies. NWMO is currently involved in the following experiments within the Mont Terri Project:

- Disturbances, Diffusion and Retention (DR-A);
- Long-term Diffusion (DR-B);
- Determination of Stress (DS);
- Gas Path Through Host Rock and Along Seals (HG-A);
- Hydrogen Transfer (HT);
- Iron Corrosion in Opalinus Clay (IC);
- Iron Corrosion – Bentonite (IC-A);
- Long-term Monitoring of Pore-pressures (LP); and
- Microbial Activity (MA).

To advance the understanding of the impact of glacial processes on the long-term performance of a DGR, the Greenland Analogue Project (GAP), a four-year field and modelling study of a land-terminating portion of the Greenland ice sheet (2009-2012), located near Kangerlussuaq (Russels Glacier), was established collaboratively by SKB, POSIVA and NWMO. The main objective is to improve the understanding of processes related to groundwater flow and water chemistry adjacent to a continental ice sheet, and thereby reduce uncertainties in future safety analyses. The Greenland ice sheet is considered to be an analogue of the conditions that are expected to prevail in Canada and Fennoscandinavia during future glacial cycles. In 2011, significant progress was achieved in the field campaign, which focused on: passive and active seismic investigations; radar mapping of ice thickness and sub-glacial features; drilling, instrumentation and sampling of a deep borehole (DHGAP04) at the front of the ice margin; and water sampling from instrumented boreholes and surface springs. NWMO staff participated in both the June and September field campaigns, which focused on surface water and groundwater sampling. The NWMO also hosted the annual GAP steering committee meeting in December. Specific details on progress in the various GAP sub-projects are summarized in Section 4.3.1.3.

NWMO continued to participate in the international radioactive waste management program of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency

(NEA). Members of this group include all the major nuclear energy countries, including waste owners and regulators. NWMO participated in the following NEA activities:

- Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (i.e., Clay Club) Annual Meeting;
- Integration Group for the Safety Case (IGSC) Methods for Safety Assessment (MeSA) Project;
- IGSC Annual Meeting and Topical Session on Gas Generation and Migration;
- Thermodynamic/Sorption Database Development Project;
- Radioactive Waste Management Committee Reversibility & Retrievability Project; and
- Radioactive Waste Management Committee.

NWMO continued its participation in BIOPROTA, the international working group on biosphere modelling. In 2011, NWMO was involved in three BIOPROTA research projects focused on ^{238}U decay chain modelling, human intrusion scenarios, and non-human biota criteria.

NWMO is an associate member of the EU FORGE (Fate Of Repository GasEs) repository gas generation and migration project as well. This work is coordinated with the SKB Äspö LASGIT and Mont Terri HG-A experiments.

2.4 INDEPENDENT PEER REVIEW

The APM Technical Program is reviewed annually by the Independent Technical Review Group (ITRG). In September 2011, the ITRG held their fourth meeting with the NWMO. They reported their findings and recommendations to the NWMO Board of Directors in December 2011. The ITRG 2011 Report and associated NWMO Action Plan can be found on the NWMO website at http://www.nwmo.ca/itrg.

3. REPOSITORY ENGINEERING

3.1 INTRODUCTION

The main objectives of the repository design development program are to: 1) develop the engineering data, models, methods and tools necessary to advance and optimize the conceptual designs for a deep geological repository (DGR) and associated systems; 2) provide the required engineering data inputs for the safety assessment of the DGR concepts; 3) support planned site characterization and investigation activities; and 4) provide engineering data to support the development of APM cost estimates.

The following sections describe the status of the repository engineering program and its achievements in 2011. This includes research and development work on used fuel integrity, container corrosion, repository sealing materials, repository design, repository monitoring, container retrieval, and transportation of the used fuel to the repository site. Also, the NWMO continues to monitor developments on used nuclear fuel reprocessing, partitioning and transmutation.

3.2 USED FUEL INVENTORY

A study to update the generic conceptual designs, implementation schedules and cost estimates for a deep geological repository for used nuclear fuel in crystalline or sedimentary rock was completed in 2011. The study was based on the previously assumed used fuel inventory estimates of 3,600,000 used fuel bundles for the base (low) case and 7,200,000 used fuel bundles for the alternate (high) case. This inventory estimate was updated and revised in late 2011, based on the currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada. For future development studies, the NWMO assumes a reference used fuel inventory of 4,600,000 used CANDU fuel bundles (Garamszeghy, 2011).

3.2.1 Used Fuel Transportation

The short-term objectives of the used nuclear fuel transportation program are to develop and evaluate options for the transport of used fuel from interim storage sites to a used fuel DGR site, and to provide engineering design and logistics to support the evaluation of potential candidate repository sites. As feasibility studies for communities in the APM program are performed, the transportation program objective is being addressed through the development of conceptual designs and illustrative case studies for each community. In the longer term, the transportation program will focus on the implementation of these conceptual designs.

3.2.2 Feasibility Studies

A feasibility study is being prepared for each community that has passed an initial screening and expresses interest in learning more about hosting a used fuel DGR. A chapter on transportation forms an integral part of the feasibility study. The transportation chapter includes identification of existing transport infrastructure from the interim storage sites to the potential host community, and presents both logistics by surface modes of transport (road, rail and water) and program costs. Discussions on the regulatory framework, transportation safety and operations are also provided. The feasibility study is designed to assess, in a preliminary way, the suitability of a community and associated site(s) to host a DGR project. The bases for the transportation system design and associated costs are derived from the updated APM engineering design and cost studies completed in 2011 (SNC-Lavalin Nuclear, 2011a, 2011b).

3.2.3 Transportation Risk Assessment

An update of a generic risk assessment for the transport of used nuclear fuel from interim used fuel storage sites to a hypothetical repository site was initiated late in 2010. The intent of this task is to update the previous assessment (OHN, 1994) through the incorporation of current system design assumptions. The risk assessment results are intended to support community engagement activities via a clear and detailed evaluation of potential risks associated with the transportation of used nuclear fuel. The assessment includes three transportation modes (road, rail and water) and addresses all conditions of transport as defined within the Canadian Transport Regulations. Work on the transportation risk assessment is expected to be completed in 2012.

3.3 USED FUEL INTEGRITY

Currently, used CANDU fuel rods in Canada are stored on an interim basis. Most of the inventory is stored in dry storage facilities at the reactor sites; the fuel bundles spend a maximum of 10 years in wet storage in the reactor bays before being transferred to interim dry storage. The integrity of the fuel bundles is important because, eventually, the fuel will need to be removed from storage facilities and transported to the site of a future APM repository.

The CANDU fuel bundle is an assembly, approximately 10 cm in diameter, of fuel elements that consist of Zircaloy tubes containing a string of cylindrical uranium pellets. The Zircaloy tubes are closed at both ends by seal-welded caps of the same material. These fuel elements are approximately 50 cm in length and 1 cm in diameter. The assembly is held together by two end-plates that are resistance welded to the fuel element end-caps. The end-plate to end-cap welds provide the structural strength required to maintain the bundle geometry and stability during and following its operating life in the reactor. An image of a 37-element CANDU fuel bundle is shown in Figure 3.1.

Figure 3.1: Photograph of a 37-Element CANDU Fuel Bundle

The structural integrity of the assembly, and the integrity of the Zircaloy cladding in each fuel element, is important for the safe handling and transportation of the fuel bundles, which may have to be repackaged for transport to the APM repository facility and then transferred from the transportation package to the used fuel containers. Extensive work has been conducted by Atomic Energy of Canada Limited (AECL), Ontario Power Generation (OPG) and the NWMO during the past three decades on mechanisms that may result in degradation or damage to the irradiated fuel during the dry storage period.

Mechanisms considered as potential causes for degradation of the used fuel bundle components are:

1) Oxidation of the cladding,
2) Fast brittle fracture,
3) Creep rupture,
4) Stress Corrosion Cracking (SCC) by Iodine,
5) Metal Vapour Embrittlement by Cesium (Cs) and Cadmium (Cd),
6) Hydrogen and Deuterium Migration in the Zircaloy,
7) Delayed Hydride Cracking, and
8) UO_2 oxidation in fuel elements with small cladding defects.

The results from an extensive body of work led to the conclusion that these processes are not expected to have a significant impact on the condition of the fuel for periods that exceed 100 years.

The potential threat for Delayed Hydride Cracking (DHC) to influence the integrity of the fuel bundles was one of the most difficult mechanisms to resolve, and it was addressed by a combination of experimental and analytical work conducted by NWMO between 2008 and 2010. A technical report summarizing the research conducted under the Used Fuel Integrity Program, and the conclusions from that work, was issued by the NWMO in 2011 (Freire-Canosa, 2011).

3.4 USED FUEL RECOVERY AND TRANSFER SYSTEMS

The Repository Engineering Fuel Transfer System Optimization Program was established during 2011. This program identified the work required during the next seven years to advance and demonstrate key fuel transfer technologies, as required for the implementation of APM. Where appropriate, the reference design for the APM facility will be advanced as technological developments are evaluated and incorporated.

A key component of the Optimization Program is a logistics study to identify and evaluate the optimum approach to recover the used fuel. The used fuel will be recovered from its current interim storage locations at the respective reactor sites, and then will be transported in a safe and secure transportation system to the DGR site, where it will be received and transferred into used fuel containers. The fuel containers will then be transferred underground and placed into the DGR.

The logistics study will review the storage technologies at the different sites and optimize the fuel recovery processes for safety and efficiency. The NWMO reference fuel recovery process identifies fuel transfer at site into standardized packages for transportation to the DGR site, as shown in Figure 3.2. This may be the best approach; however, used fuel is currently stored at seven different locations in four different provinces utilizing different technologies. Figure 3.3 shows a number of alternative approaches for the recovery of used fuel from each interim storage site and its transfer to the repository site.

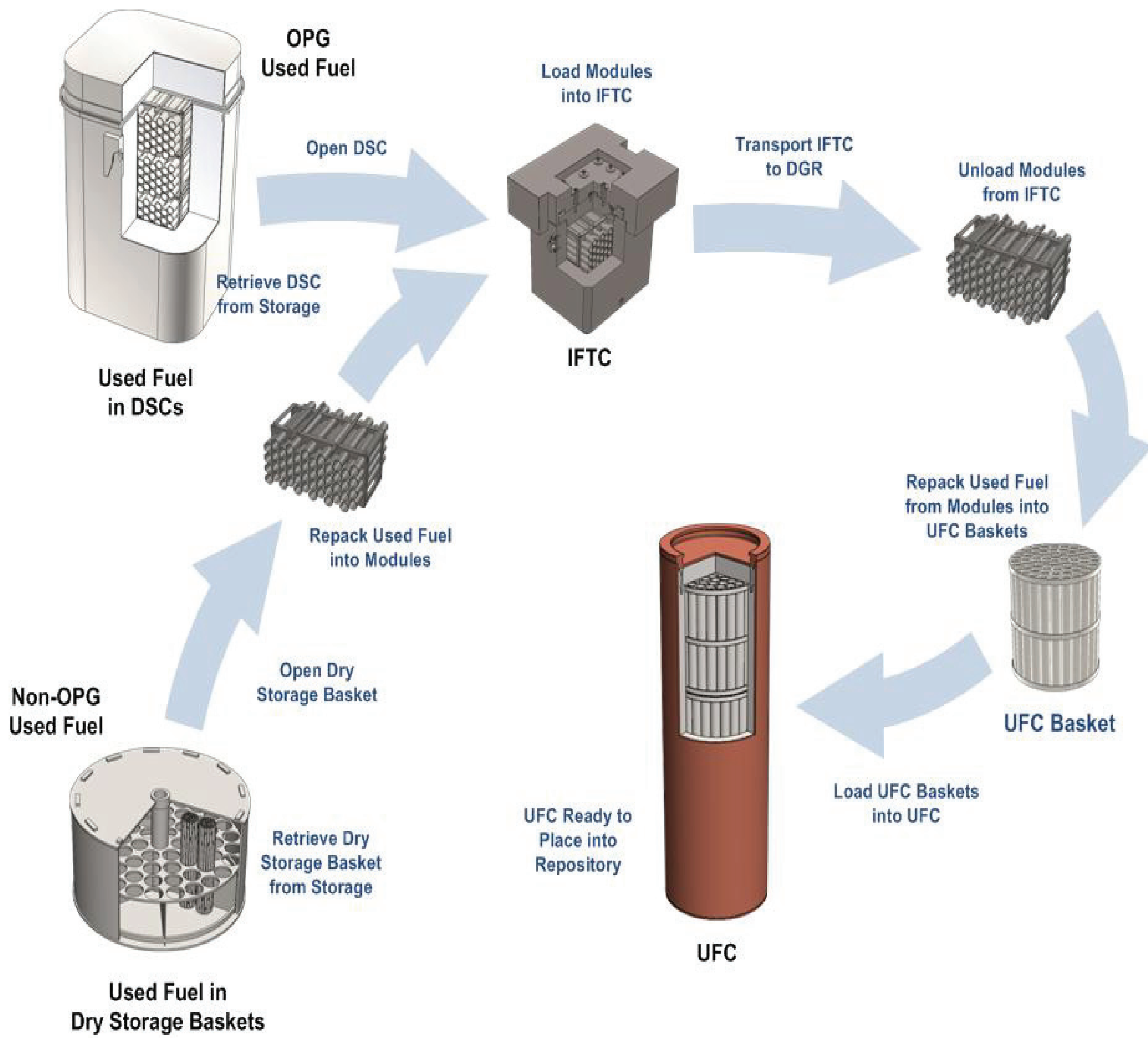

Figure 3.2: Flow Chart Illustrating a Process for Recovery and Transport of the Canadian Used Nuclear Fuel Stored at Reactor Sites; Dry Storage Container (DSC), UFC (Used Fuel Container), Irradiated Fuel Transfer Cask (ITFC)

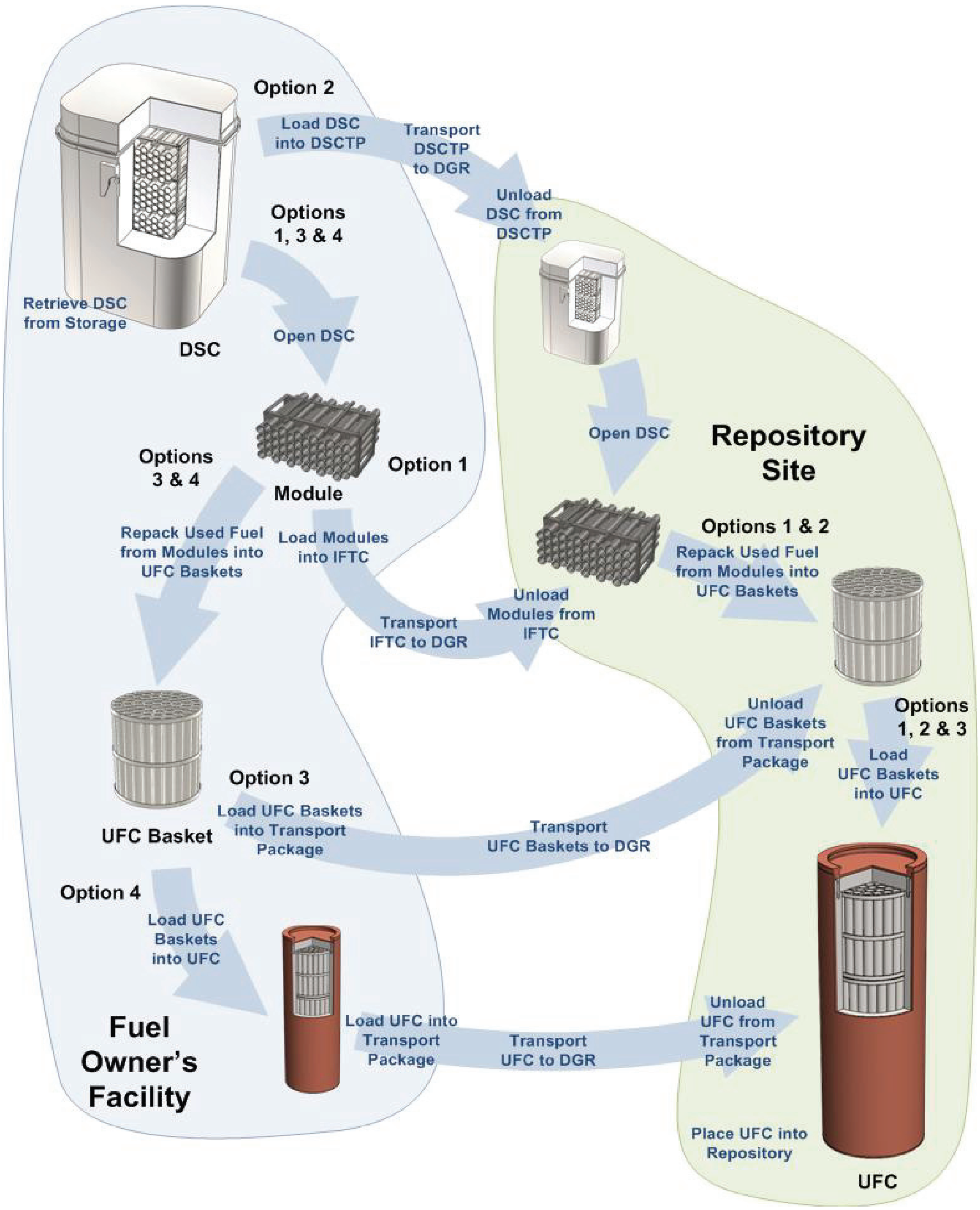

Figure 3.3: Flow Chart Showing Alternative Approaches to the Recovery of Used Fuel from Each Site and Transfer to the APM Facility; Dry Storage Container (DSC), Dry Storage Container Transport Package (DSCTP), UFC (Used Fuel Container), Irradiated Fuel Transfer Cask (ITFC)

3.5 USED FUEL CONTAINER (UFC)

NWMO's existing used fuel container (UFC) designs have been developed at a conceptual level, based on performance requirements defined for generic repository designs developed for hypothetical sites. These container designs are based on engineering concepts and corrosion research results, but were not developed to a level such that they could be manufactured and demonstrated by 2011. In 2011, a used fuel container development program was prepared, consistent with the needs of the APM implementation process. The development work, to be conducted over the next several years, will examine container manufacturing processes and technologies and will advance the engineering design (to include the building of prototypes and demonstrations of container performance).

Both copper and steel have been considered as potential corrosion barrier materials for used fuel containers. A typical geometry for the conceptual design of a dual-vessel copper and steel used fuel container is illustrated in Figure 3.4.

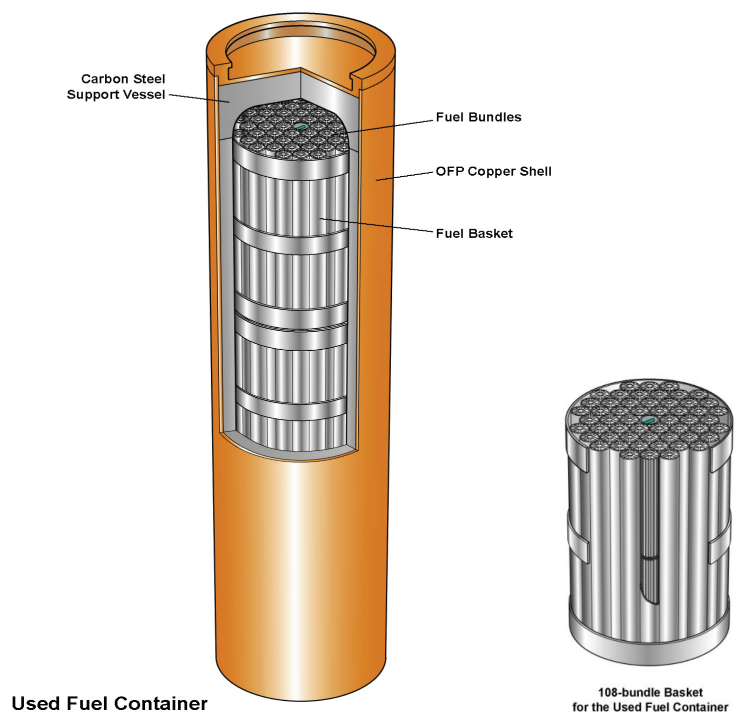

Figure 3.4: Dual-Vessel Copper and Steel Used Fuel Container and Fuel Basket; Oxygen-Free Phosphorous-doped (OFP)

NWMO is carrying forward several container design concepts, which include: a) copper shell with steel inner vessel; b) steel only container; and c) steel vessel with an externally applied copper corrosion barrier. The final selection of a container type will depend on geology and geochemical properties of the selected site for an underground repository. In the case of the dual copper-steel vessel, several material process options are available for the external corrosion barrier, including an outer copper vessel similar to that of previous designs, or the application of metallurgical coating technologies to bond the copper directly onto the steel vessel. The objective of the plan is to identify an optimized design and develop detailed specifications for prototype manufacture by 2014.

3.5.1 Used Fuel Container Design

In 2011, NWMO initiated several engineering and development programs that will provide key inputs into the UFC design and manufacturing technology. A container sizing study was initiated with Babcock & Wilcox Canada, which will provide engineering input into the identification of optimum size alternatives considering factors such as materials, processes and inspection methods related to component fabrication and performance. The study will also assess process efficiencies related to production volume, and identify risks associated with the first-of-a-kind nature of these designs.

Related to the sizing study, there is also a weld development program associated with the sealing of the container. Closure welding of a vessel containing highly radioactive fuel requires remote welding and inspection capability, and, as such, the selection of a suitable weld design/process, followed by detailed development and qualification, is required. NWMO has initiated investigations in these areas with several vessel fabricators and companies experienced in remote nuclear welding. A comprehensive program, including welding trials with mock-up assemblies, is planned for 2012.

A program was also initiated in 2011 to assess the use of copper coating technologies as a method to build a corrosion barrier on the container exterior surface. This program is evaluating several technologies including cold spray, laser clad overlay and electrodeposition. Leading researchers from the University of Windsor, University of Ottawa, McGill University, University of Western Ontario, and the National Research Council of Canada, are involved in the process development, metallurgical, corrosion, and non-destructive inspection aspects of this program.

To complement the experimental research, NWMO has initiated the development of analytical tools for modelling the different container processes and assessing container performance. A mechanical integrity model is being developed to verify the performance of the UFC under service conditions. The model will utilize a conservative design methodology, in accordance with relevant national and international regulations and standards. The complexity and innovative nature of the project will require advanced design techniques, including non-linear Finite Element Analysis that will incorporate thermal effects, dissimilar material bonding, and material creep mechanisms. The program will leverage expertise from leading industrial experts and researchers in the fields of fracture mechanics and structural design analysis. Experimental testing will be utilized to validate the model and to further assess the safety function of the container(s).

3.5.2 Used Fuel Container Corrosion

3.5.2.1 <u>Copper Corrosion</u>

Two technical reports on copper corrosion were published in 2011. The first report discusses the state of knowledge on copper corrosion under conditions representative of groundwaters in crystalline rock environments and also includes a status report on Stress Corrosion Cracking (SCC) of Oxygen-Free Phosphorous-doped (OFP) copper in nitrite and ammonia solutions (Litke and Ikeda, 2011). The second report describes the results of corrosion studies for copper used fuel containers under low salinity conditions (Kwong, 2011).

Litke and Ikeda (2011) provide a summary of the conclusions from work conducted during 2009-2010 that was designed to enhance the understanding of SCC in copper in the presence of nitrites and ammonia, two possible SCC agents produced by microbial activity that may be present in a deep geological repository environment. The report concludes that at low concentrations of nitrite (<0.01 mol/L), SCC does not initiate, and that it is suppressed at higher nitrite concentrations (>0.1 mol/L) with a chloride concentration of 1:1. Ammonia-induced SCC appears to require a threshold of 0.3 mol/L ammonia; however, suppression by chloride did not occur for chloride solutions below 1 mol/L. These results are consistent with conclusions from previous work indicating that the environment of a DGR is not conducive to SCC events because the potential SCC agents occur at much lower concentrations than the observed threshold values.

Kwong (2011) summarizes the state of knowledge of copper corrosion in a DGR environment under low salinity conditions. The report reviewed the results from both experimental and modelling work conducted during the past 20 years and concluded that the maximum loss of wall thickness in a UFC copper shell is not expected to exceed 1.27 mm over a period of 1,000,000 years. This result was based on conservative estimates of thickness loss of 0.17 mm from uniform oxidation, 0.1 mm localized under-deposit corrosion, and 1 mm as a result of the diffusion of corrosion agents towards the container surface. The primary corrosion agents were sulphides produced by microbial activity away from the container. A broad-based review of the results from the work on copper corrosion in low salinity environments has been initiated at the international level and will be completed in 2012.

Other on-going work initiated in 2011 involves the investigation of copper corrosion phenomena in high salinity environments, consistent with groundwaters found in some sedimentary and very deep crystalline formations in Canada. Thermodynamic calculations have previously shown that copper may be susceptible to anaerobic corrosion at high temperature (~100°C), high salinity (> 3 mol/L), and slightly acidic to acidic conditions (pH < 6). NWMO has taken steps to study corrosion under these conditions. The current understanding is that copper undergoes the following (anaerobic) reaction:

$$Cu + 3Cl^- + H^+ \rightarrow CuCl_3^{2-} + 0.5\ H_2.$$

However, the thermodynamics of this reaction are not fully understood. The focus of this on-going study is to identify all possible species that may be produced as a result of the reaction. The corrosion rates are determined by measuring the production of hydrogen and by assessing surfaces for corrosion damage following specified exposure periods. The intent is to determine temperature, pH, and concentration thresholds for the corrosion process. The experiments include voltammetric scans to identify the potential regions where various reactions occur, as well as open circuit potential measurements.

The open circuit potential (E_{OCP}) is found to change with the chloride concentration, but does not vary with temperature, as illustrated in Figure 3.5, where potentials are expressed relative to the Standard Calomel Electrode (SCE). A shift to more negative potentials would be consistent with increased chemisorption of Cl^- on the copper surface. Differential capacitance measurements will be carried out to confirm whether or not chemisorption occurs.

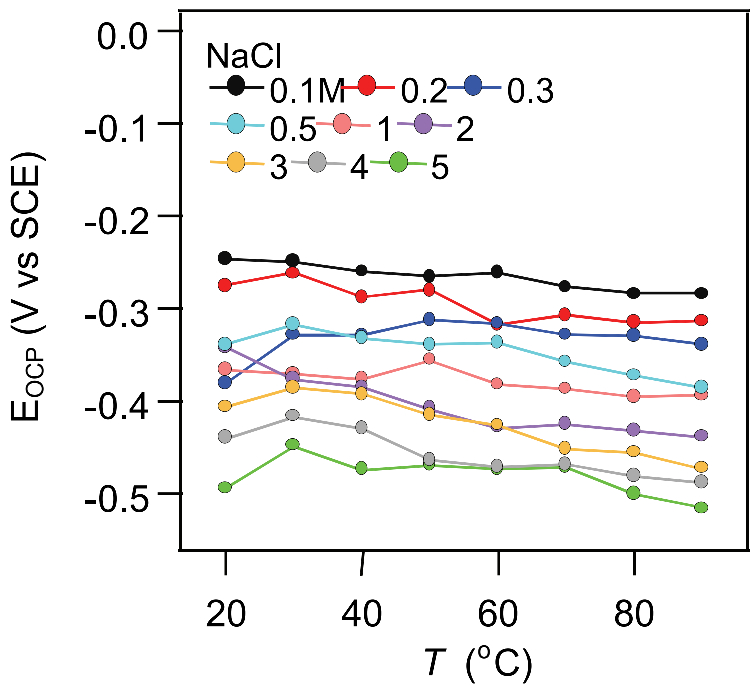

Figure 3.5: Copper Open Circuit Potentials Measured as a Function of Temperature and Chloride Concentration

The voltammetric scans that measure current density (*j*) as a function of electrochemical potential (E), indicate that an increase in chloride concentration strongly promotes copper dissolution during anodic (oxidizing) scans, as illustrated in Figure 3.6 for experiments conducted at 90 °C. Similar measurements (not shown) at cathodic (reducing) potentials below –0.6 V SCE indicate that H_2O reduction is accelerated by temperature but is not particularly dependent on chloride concentration. From the combination of results, it may be concluded that chloride chemisorption, which increases with chloride concentration, could couple to an accelerated H_2O reduction, and facilitate Cu dissolution (i.e., corrosion) reactions. Such a combination would potentially destabilize the Cu corrosion barrier; however, there is no evidence of corrosion of the copper in the unperturbed (i.e., open circuit) condition. This work, initiated in 2011, is scheduled to be completed in 2013.

NWMO has also undertaken to adapt its existing customized models and codes so that they can be executed using commercially available platforms such as COMSOL Multiphysics. COMSOL is a generic three-dimensional finite element modelling software package that allows users to represent various geometries and solve coupled equations. This work is on-going, and is aimed at enhancing NWMO capability to model copper corrosion phenomena in used fuel containers.

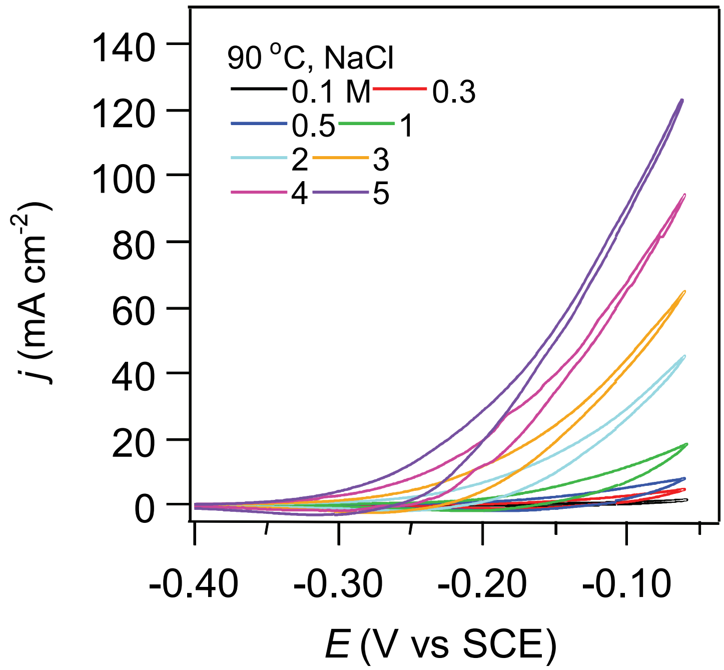

Figure 3.6: Effect of Chloride Concentrations on the Cu Dissolution Currents Measured in Voltammetric Scans

3.5.2.2 Steel Corrosion

Planning for long-term measurements of corrosion of steels, and welded steels of grades suitable for used fuel containers, was undertaken in 2011. The schedule for these experiments to be conducted at Mont Terri in Switzerland, in cooperation with ANDRA and NAGRA, will consist of the placing of both machined steel and welded steel coupons into compacted bentonite within stainless steel canisters that allow groundwater infiltration. These long-term experiments, to be initiated in March of 2012, will span several years, with periodic extraction of these pressure vessels at 1, 1.5, 2.5, 3, 5, 7 and 10 year intervals.

3.6 USED FUEL PACKING PLANT

An important component of the APM surface facilities is the Used Fuel Packing Plant (UFPP). The UFPP will receive used fuel shipped from the reactor sites and new UFCs that will be shipped from a dedicated manufacturing facility. The operations in the plant will include: 1) transferring of the used fuel from the transportation casks into UFCs, 2) seal-welding of the UFCs, 3) filling the container inner volume with an inert gas, 4) conducting a final inspection of the sealed container, and 5) staging the container for transfer to the underground repository. The used fuel transfer technology will be unique to the packing plant. An illustration of the reference design concept for the UFPP is shown in Figure 3.7.

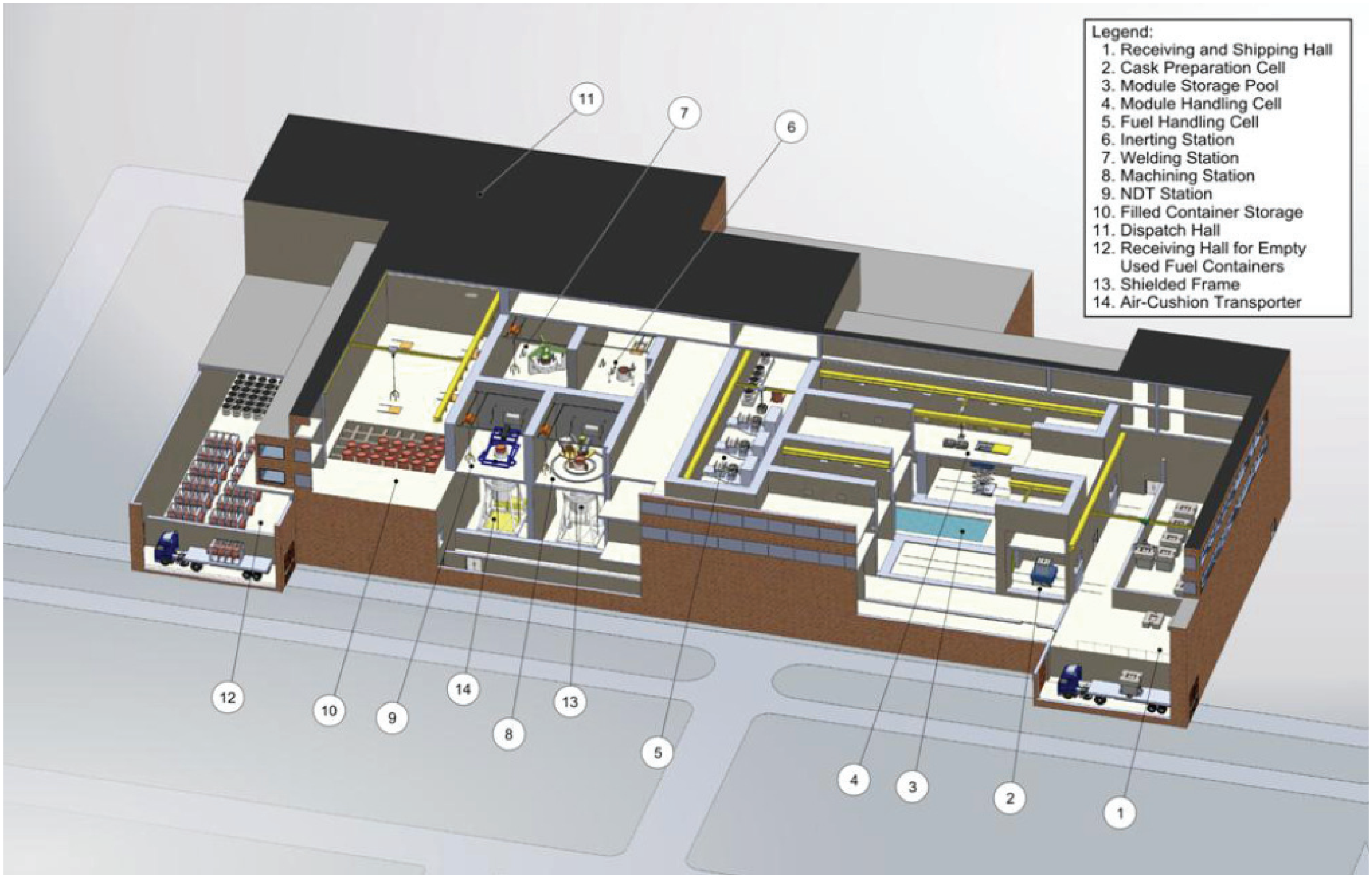

Figure 3.7: Design Concept for the Used Fuel Packing Plant

A conceptual design for a used fuel transfer line has been developed. The fuel transfer operations will take place in a dry environment and, therefore, they must be carried out within a shielded containment structure (hot cell). These operations include removing the used fuel modules from the transportation cask and transferring the fuel from the modules into UFC baskets. The transfer system is illustrated in Figure 3.8 and the UFC loading operation is described below. The routine steps for transfer of used fuel bundles from modules into a UFC are as follows:

- Receive loaded fuel transportation cask;
- Remove the loaded used fuel modules from fuel transportation cask;
- Place a loaded module on the module positioning cart;
- Lock cart in the transfer position;
- Place empty UFC fuel basket on used fuel tilt table;
- Align loaded used fuel module tube, used fuel unloading unit and used fuel bundle transfer unit (1, 2 & 4 on Figure 3.8);
- Push two fuel bundles from module tube into bundle transfer unit;
- Conduct visual inspection with charge-coupled device (CCD) cameras;
- If fuel bundles pass inspection, align transfer unit with UFC basket tube;
- Push the two fuel bundles into the basket tube (8);
- Damaged bundles are transferred to the damaged bundle basket (9);
- Repeat the operation until the basket is fully loaded;
- Rotate the tilt table such that the fuel bundles are in the vertical position; and
- Lift the loaded basket from the used fuel packing cell and place it into a UFC.

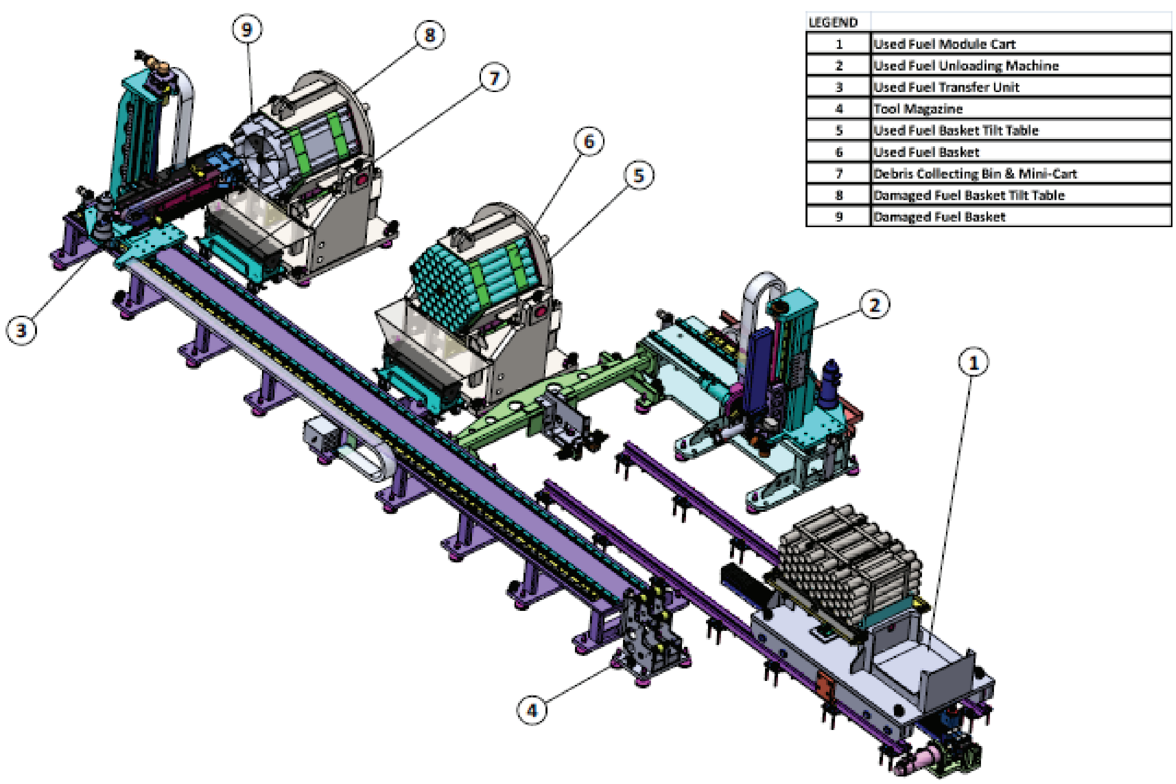

Figure 3.8: Process and Equipment for the Transfer of Used Fuel from Storage Modules to UFC Baskets

Further development and demonstration of the fuel bundle transfer system design is planned for the period 2012-2018.

The UFC will require a seal weld for containment and isolation of the loaded used fuel. A concept for the UFC welding hot cell has been generated. Initial screening activities are reviewing different applications of closure technologies, including the use of laser welding technologies to develop a robust closure weld. As with the fuel transfer hot cell, the closure weld process will require a hot cell to perform the necessary operations. Several concepts reviewing both equipment and hot cell layouts have been developed. As the UFC design matures, refinement and demonstration of closure technologies will be pursued.

3.7 BUFFER AND SEALING SYSTEMS

In 2011, NWMO continued its program to assess the properties of bentonite-based sealing materials through laboratory and modelling studies. The work program included: consolidation and triaxial testing; bentonite component swelling studies; and, an assessment of as-placed bentonite pellets. Currently, the following bentonite-based sealing materials are being considered for use in a DGR:

- Highly compacted bentonite (HCB) – 100% bentonite clay;
- Bentonite-Sand Buffer (BSB) – 50% bentonite and 50% sand by mass;
- Dense Backfill (DBF) – 70% crushed granite, 25% lake clay and 5% bentonite by mass;
- 70/30 Bentonite Sand (70/30BF) – 70% bentonite and 30% sand by mass;
- Light Backfill (LBF) – 50% bentonite and 50% crushed granite by mass; and,
- Gapfill (GF) – 100% bentonite clay fabricated in the form of dense pellets.

In 2011, a triaxial testing and consolidation program continued to assess the properties of a 70/30 bentonite sand mix (70/30BF), which is the reference bentonite material for the APM DGR shaft seal in both crystalline and sedimentary rock. This work is underway in the geotechnical laboratories at Royal Military College of Canada and the University of Manitoba. Six (6) consolidation tests were conducted and three (3) triaxial tests were initiated in 2011(these remain in the saturation phase at present due to the long saturation times of the 70/30BF material). The highest swelling pressures were observed in the tests using distilled water, as expected.

In addition to the above noted testing programs, the NWMO has also contributed to the SKB Backfill and Closure (BACLO) project (Kim and Priyanto, 2011). This work was conducted as part of a collaborative (SKB, POSIVA and NWMO) study on piping, erosion and backfill stability performed by several laboratories and at the Äspö Hard Rock laboratory in Sweden. Photographs of the laboratory apparatus are shown in Figure 3.9. This program investigated the manner in which water supplied from the rock will be taken up by the densely compacted backfill blocks and bentonite pellets in a setting configured to represent the tunnel fill in a placement room of a deep geological repository (using the In-Floor Borehole placement method; refer to Figure 1.1).

A total of 17 testing cells were installed at AECL's geotechnical laboratory in order to examine the process of water uptake and volumetric equilibration of backfill clay blocks in contact with clay pellets. These tests consisted of two different assemblies (i.e., Friedland clay blocks-bentonite pellets and Asha clay blocks-bentonite pellets) and two different groundwater compositions (salinities of 1.0% and 3.5%). The cells were dismantled at intervals of 3, 9 and 27 months and water content and volume changes were observed. The test results indicate that a system consisting of two similar mineralogical materials will come to a homogeneous density state. The two different pore fluid salinities had little effect on the apparent rate of system equilibration.

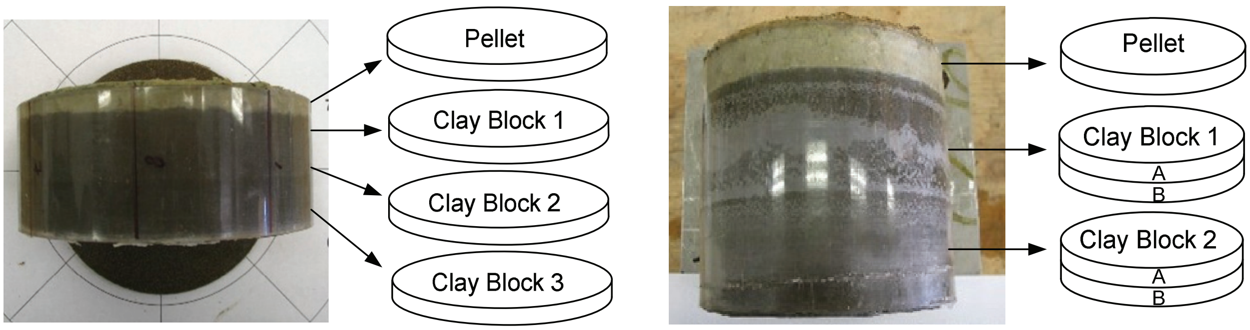

Figure 3.9: Sampling Layers of Short (left) and Long (right) Specimens Surrounded by Plexiglas Sleeves

A pellet optimization study was carried out to improve the quality of bentonite-based pellets to better meet the heat transfer requirements of the placement concepts being considered by NWMO, POSIVA and SKB. A range of pellet sizes and shapes, as well as the effects of various volumetrically inert fillers on the properties of bentonite-based materials, were examined. Several different bentonite materials of interest to NWMO, SKB and POSIVA were examined, as well as illitic clay and fine quartz-sand fillers. Filler contents of 10, 25 and 50% by weight were tested in order to assess the potential utility of such materials in: 1) filling gaps that may exist between the UFC and the rock in the In-Floor Borehole geometry, and 2) tunnel backfilling applications.

3.8 USED FUEL CONTAINER AND BUFFER MATERIAL TRANSFER SYSTEMS

In 2011, the NWMO completed an update to the generic conceptual designs, implementation schedules and cost estimates for an APM approach that includes a DGR for used fuel in crystalline or sedimentary rock. The update includes associated facilities at the repository site and the systems for transporting used fuel from current storage locations to the repository site. The design update also includes concepts for filling the used fuel containers, manufacturing the bentonite based products, and moving materials around the site. Concepts for the transport and placement of the UFCs in the repository have been developed based on the practical application of known technologies.

At the UFPP the filled UFCs will be sealed, inspected and dispatched for placement in the underground repository. Adjacent to the filled UFC storage cell is a dispatch hall for the loading of filled UFCs into shielded transfer casks before transport to the repository. The filled UFCs, and the manufactured buffer rings and disks for the crystalline case, or buffer pedestal for the sedimentary case, would be transferred from their respective surface facilities to the repository level via the main shaft for the UFCs and the service shaft for the bentonite based manufactured products. Underground vehicles will then convey the products to the placement rooms.

All equipment, parts and materials for UFC placement (with the exception of the UFCs themselves) would be moved by rail in the access drifts, crosscuts and placement rooms, using flatcars and materials handling cars. The UFCs will be placed on specifically designed rail flatcars at surface and transported in the Main Shaft to the underground shaft station. For a crystalline rock repository, for example, the UFC transfer cask, complete with UFC, will be transported by rail from the shaft area to the active placement room and moved into place beneath the placement machine and over the target borehole. The UFC will be rotated to a vertical position and coupled to the shielding barrier overlying the borehole. Doors from the transfer cask and shielding barrier will be opened and the UFC will be lowered by winch into the borehole within the bentonite rings. Once the UFC is in place, the shielding barrier opening to the borehole will be closed and the empty UFC transfer cask will be removed from the placement room.

3.9 UNDERGROUND REPOSITORY TECHNOLOGY

The development of the layout for the underground repository consisted of conceptual designs for an Underground Demonstration Facility (UDF), where the prototype equipment could be tested in an underground setting prior to the commencement of operations, and for the layout of the placement panels, as well as the spacing of the UFCs and the placement rooms.

The UDF has been designed as a stand-alone testing location near the Main and Service Shafts at one end of the underground repository. The UDF could subsequently expand to encompass the perimeter drifts around the outside of the repository to allow for the on-going study and testing of the host geosphere rock mass. The UDF could support the long-term demonstration and monitoring of container placement and sealing system tests, and could provide a potential training area for DGR employees.

The basic arrangement of the DGR involves a series of parallel, dead-end placement rooms, organized into panels. All underground openings (access drifts, etc.) will be carried out by controlled drill and blast methods, with the exception of the placement boreholes which will be formed with a boring machine. The placement rooms will have an arched shape of nominal dimensions 5.5 m wide by 5.5 m high.

Using thermal/mechanical modelling tools, the UFC and room spacings are found to be dictated by the requirement to limit the maximum temperature of the buffer materials surrounding the UFCs. For the design update, a spacing of 4.2 m (centre to centre) between placement boreholes, and a parallel placement room spacing of 40 m (centre to centre), was adopted. Refinement of the placement room spacing is on-going.

3.9.1 Repository Monitoring

The work on repository monitoring conducted during 2011 contained two different components: a seal monitoring experiment, and the development of a monitoring work program for the APM project.

The experimental component consisted of the continued monitoring of an instrumented shaft seal placed in the access shaft of the decommissioned AECL Underground Research Laboratory near Pinawa, Manitoba. Monitoring of the seal was initiated in 2010 and it is intended to continue for several years. A current agreement between AECL, POSIVA, SKB and NWMO will fund this work until the end of 2013. At the end of that agreement, the need for continuous monitoring of the seal will be evaluated and a decision will be made on the possible extension of the agreement.

Preliminary work on development of a repository monitoring work program, consistent with the goals of the Canadian APM project, was initiated in 2011. The intent of this initial phase of the work is to lay a theoretical basis for the task and to define the scope of the work for the next several years. A scope of work for the period 2012-2018 is being developed.

3.9.2 Used Fuel Container Retrieval

The subject of container retrieval was addressed in a preliminary manner in the APM design and cost estimate update completed in 2011. Using the concepts put forward in the primary design report (SNC-Lavalin Nuclear, 2011c) as a starting point, two separate NWMO reports describing container retrieval systems and retrieval operations, specific to repository designs for crystalline and sedimentary rock, were drafted in 2011. These reports will be issued in 2012 and address the technological aspects, as well as the philosophical basis, for a retrieval operation and its significance for the implementation of APM.

3.10 REPROCESSING AND ALTERNATIVE WASTE MANAGEMENT TECHNOLOGY

In 2011, work continued in several international programs to review and assess the implications of advanced fuel cycles on waste management issues, including reprocessing, partitioning and transmutation (RP&T). Comprehensive technical reports were published in 2011 by the International Atomic Energy Agency (IAEA, 2011), the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA, 2011), the Electric Power Research Institute (EPRI, 2010a, 2010b), the US Blue Ribbon Commission on America's Nuclear Future (US BRC, 2011a, 2011b, 2011c, 2011d), the US Government Accountability Office (US GAO, 2011) and the US Nuclear Waste Technical Review Board (US NWTRB, 2011a, 2011b). Additional strategic reviews were published by the EPRI and the UK Nuclear Decommissioning Authority (UK NDA, 2011). These technical and strategic reviews, which were prepared independently by various teams of international experts, all reached similar conclusions, many of which are consistent with those stated in previous NWMO watching brief reports (Jackson, 2008, 2009, 2010).

- Some form of deep geological repository is required, regardless of the fuel cycle, in order to be able to deal with long-lived radioactive wastes.
- While RP&T has the potential to reduce the volume of used nuclear fuel and high-level waste for placement in a deep geological repository (when combined with advanced fuel cycles using fast reactors), it also significantly increases the quantity of long-lived low- and intermediate-level waste (which also requires a deep repository for its long-term management) and does not significantly reduce the underground footprint of the repository.
- Advanced fuel cycles are, at least, many decades away from being ready for commercial energy production due to the time required for the technical research, development and demonstration of the reactor technologies. Broad public acceptance issues are also likely to inhibit their demonstration and deployment in the near term.
- The lifecycle cost of advanced fuel cycles is higher than once-through fuel cycles, due to the high costs of developing and constructing the new generation reactors, reprocessing facilities and fuel fabrication plants. If such fuel cycles could be developed, the cost and project risks for implementing them on a commercial scale would currently make them very unattractive for utilities to deploy.
- Some countries currently engaged in fuel reprocessing (such as the UK) are considering discontinuing this practice due to the lower cost option of direct placement of used fuel in a deep geological repository.

Basic technical research is progressing in a number of advanced reactor and fuel cycle areas, including RP&T, and such research has been reported at a number of conferences, such as ICENES (15th International Conference on Emerging Nuclear Energy Systems) and GLOBAL 2011 (international conference focused on the nuclear cycle and future nuclear systems). A wide variety of work is being carried out on such topics; however, the research to-date demonstrates that the technology is still far away from practical implementation because much of the work has not progressed beyond the laboratory environment. There are many basic technical challenges facing these advanced technologies, such as the development of suitable materials to contain the very high temperatures, pressures and/or corrosive nature of the process fluids while operating in the high-energy and high-flux neutron fields required in the core for these reactors, as well as the development of suitable fuel matrices.

4. GEOSCIENCE

4.1 INTRODUCTION

In collaboration with technical experts, both in Canada and internationally, the NWMO is pursuing an active technical program, which addresses a wide range of technical topics related to the development of DGRs for used nuclear fuel. The primary objectives of the NWMO's geoscience technical program are to: 1) ensure preparedness to conduct site characterization activities for the purpose of evaluating the adequacy of potential candidate sites in both sedimentary and crystalline environments for a deep geological repository (DGR); 2) advance understanding of the geosphere in terms of stability, predictability, and resilience to long-term perturbations; 3) substantiate the role of geoscience in establishing support for a DGR safety case; and 4) maintain a high level of competency and a credible Canadian based technical program, by involving both national and international specialists, consultants and universities in the development of the geoscience approach for evaluating and interpreting geosphere properties, groundwater system behaviour and predictions of long-term geosphere and long-term DGR performance.

The geoscience program is continually striving to achieve these objectives by focusing on: 1) the development of both plans and methods to assess the suitability of potential candidate sites for a DGR in willing host communities, and 2) on-going refinement of the understanding of geosphere processes related to the long-term stability and performance of a DGR. These objectives are achieved through a multidisciplinary approach involving the coordinated effort of research groups drawn from Canadian universities, consultants, federal organizations and international research institutions. The following sections outline NWMO's geoscience activities in 2011.

4.2 METHODS FOR SITE INVESTIGATION

In 2011, NWMO continued to develop readiness for detailed surface-based site investigations, which will eventually be conducted for selected, willing host communities identified during the site selection process (see Chapter 1). NWMO continued to develop and refine methods for characterization of geochemistry (Section 4.2.1), petrophysics (Section 4.2.2), radionuclide transport (Section 4.2.3), microbiology (Section 4.2.4), geomechanical properties (Section 4.2.5), and seismicity (Section 4.2.6). Work programs and international partnerships focused on assessing long-term geosphere stability are summarized in Section 4.3.

4.2.1 Matrix Porewater Extraction and Geochemical Analysis

In 2011, the NWMO continued to explore the development of methods to enhance porewater (i.e., groundwater within the connected pore space between mineral grains in low-permeability sediments or rocks, that does not flow readily into and cannot be sampled from surface-drilled boreholes) extraction from low permeability rock formations. Enhancement of methods used for porewater extraction is focused on vacuum distillation and crush and leach, in collaboration with the University of Ottawa, as well as an innovative filter paper technique being explored at the University of New Brunswick. In addition, the diffusive exchange technique for measuring the isotopic compositions of saline waters, being developed at the University of Bern, was refined.

The vacuum distillation and crush and leach techniques were applied successfully to the pore fluid characterization program for the Ontario Power Generation Low & Intermediate Level

Waste (L&ILW) DGR project at the Bruce nuclear site (Clark et al., 2010a, 2010b, 2011). The on-going work program continues to evaluate and benchmark isotopic (vacuum distillation) and geochemical (crush and leach) analysis techniques that can be used in future site characterization activities in both crystalline and sedimentary rock. The method is being further refined to assess the effects of 1) grain size and 2) the inclusion of clay-bound waters on the results of porewater analyses. In support of APM, analytical methods and protocols will be recommended for use in different rock types, with an aim to significantly expand Canadian expertise in the area of porewater extraction techniques.

The filter paper technique is in its preliminary stages of assessment. The technique uses capillary action to extract small quantities of porewater onto absorbent, low chemical-background papers sandwiched between rock core segments. The porewater extracted from low permeability sedimentary rock and collected on the filter paper is analyzed for solute concentrations using gravimetric and X-ray fluorescence (XRF) techniques. The technique requires very small volumes of porewater (less than 50 microlitres) to provide enough solute mass for accurate XRF analysis. Weighing and drying the paper, followed by analysis of the composition of the elements by XRF, may provide a means of quantifying the in-situ composition of the major and minor solutes directly (Na, K, Ca, Mg, Sr, Cl and Br) in high salinity porewater, without any need for sample dilution, crush and leach, or reliance on measurements of sample porosity, which would effectively reduce uncertainties in the measured porewater compositions by removing potential analytical artefacts.

A two-year work program with the University of Bern was completed in 2011. The work program was established to evaluate and benchmark an adapted diffusive exchange technique for measuring the stable isotope compositions ($\delta^{18}O$ and $\delta^{2}H$) of saline matrix porewaters and to document the experimental method development. Testing of this technique focused on highly saline porewaters, such as those often found in deep Canadian crystalline and sedimentary systems. The work program provided an opportunity to determine the applicability of the technique to rocks with a range of mineralogies, porosities and porewater salinities. A comprehensive technical report, discussing the method development, experimental protocols, and the strengths and limitations of the technique, will be issued in 2012.

4.2.1.1 Natural Analogue Study

A natural analogue study, using data collected at the Bruce nuclear site as part of the L&ILW DGR project, began in 2011, in collaboration with researchers from the University of New Brunswick, the University of Ottawa, the University of Waterloo and the United States Geological Survey (USGS). The study is focused on the evolution of both pore fluid chemistry and in-situ hydraulic pressures. Numerous measurements of hydraulic pressure were collected from multi-level Westbay systems installed in drilled boreholes at the Bruce nuclear site. An extensive geochemical dataset was collected as well (including $\delta^{18}O$, $\delta^{2}H$, major ion concentrations, $^{87}Sr/^{86}Sr$ and gases – concentrations and isotopes methane and helium) from the analysis of fluids and brine from all formations within the sedimentary sequence. Integration of the hydraulic and geochemical datasets provides opportunity to explore and constrain the processes and mechanisms governing solute migration and pore fluid evolution on time frames of geologic relevance. This approach of developing a site-specific analogue for mass transport has been demonstrated internationally as a useful tool in assessing groundwater system stability (e.g., Mazurek et al., 2011), a key aspect of a DGR safety case.

4.2.2 Determination of Petrophysical Properties

Any argument regarding the feasibility of a host rock to safely contain and isolate radioactive waste must include an understanding of the transport properties of the rock mass. To aid in developing this understanding, NWMO introduced a petrophysical research program in 2011. Petrophysical analysis provides a means to directly or indirectly determine the parameters that influence pore fluid transport, particularly porosity, permeability and pore fluid saturation, within both sedimentary and crystalline environments. The objective for 2011 was to determine the suitability of commercial laboratory petrophysical methodologies – typically implemented in support of the oil and gas industry for reservoir resource assessment – for characterization of the extremely low porosity and low permeability rock formations considered for a deep geologic repository.

A work program with TerraTek, a subsidiary of Schlumberger, was initiated in the fall of 2011. TerraTek has developed a proprietary method of petrophysical characterization, which is specifically suited for the analysis of low porosity and low permeability rocks, such as those encountered in the sedimentary environment beneath the Bruce nuclear site. Core samples collected from Ordovician sedimentary units in borehole DGR-8 at the Bruce nuclear site were subjected to detailed measurements of rock permeability (pulse decay method), bulk and grain density, gas-filled porosity, fluid saturation (oil, water and clay-bound water), and effective total interconnected porosity. Additional analyses undertaken in 2012 will include measurement of Total Organic Carbon content, Rock-Eval Pyrolysis, and bulk and clay-size fraction determination using X-Ray Diffraction.

The final results of TerraTek's petrophysical analyses are expected by the end of the first quarter in 2012. With the results, far-field two-phase flow and transport processes, and the influence of laboratory artefacts and scale dependency, may be better assessed.

4.2.3 Assessment of Radionuclide Transport Processes

A key issue for DGR performance assessment of the long-term containment of used nuclear fuel is the understanding of dominant solute transport processes for radionuclides. Within very low hydraulic conductivity crystalline or sedimentary formations, transport processes are dominated by diffusion. Sorption of solutes onto mineral surfaces is another important mechanism for retarding radionuclide transport. Hence, measurement of diffusion and sorption properties is important for demonstrating the containment and isolation capabilities of low permeability rocks, and for increasing confidence in the DGR safety case. The activities undertaken in 2011 are described below.

4.2.3.1 Diffusion

Diffusion is considered to be the dominant mechanism for solute transport in low permeability geological formations. The diffusion coefficient is an important parameter for numerical simulation of radionuclide transport. Previous NWMO work programs, in collaboration with the University of New Brunswick, successfully developed an X-ray radiography technique to quantify diffusion coefficients using conservative iodide and tritium tracers (Cavé et al., 2009a, 2009b). The x-ray radiography technique was expanded to quantify diffusion-reaction processes using a non-conservative tracer, Cesium (Cavé et al., 2010). This technique was then applied to investigate the reactive transport of non-conservative solutes in a sorption and diffusion dominated sedimentary rock system (Cavé et al., 2010). Reactive transport modelling, coupling diffusion and ion-exchange, correlated well with experimental data and was successfully used to quantify the cation exchange capacity of intact rock samples.

The X-ray radiography method was further developed in 2011 by improving the calibration procedure for radiography measurements in order to better quantify diffusion-reaction processes for non-conservative tracers. The improved X-ray radiography technique was used to measure diffusion coefficients for the Opalinus Clay from the Mont Terri Underground Laboratory (http://www.mont-terri.ch) with both conservative and non-conservative tracers. The diffusion coefficients measured using the X-ray radiography technique were compared with previously reported values measured in both laboratory and in-situ field-scale diffusion experiments. A report will be available in 2012.

Through-diffusion measurements were also performed at the University of New Brunswick on shale and limestone rocks using HTO and iodide tracers, under confining pressures (up to 12-17 MPa). The diffusion coefficients determined under the confining pressure are lower than the diffusion coefficients determined at ambient pressure.

Investigation of the impact of partial saturation on diffusive transport in low-permeability sedimentary rocks was initiated in 2011. A review of measurement techniques for determining partial saturations was conducted. The pressure-difference method was used to introduce gas into the rock pores, and the gas/brine partial saturation was determined using the X-ray radiography method. A method to measure the diffusion coefficients for partially-saturated rock samples will be developed in upcoming work programs.

4.2.3.2 Sorption

Sorption is a potential mechanism for retarding radionuclide transport to the biosphere. Gaps in sorption data for saline solutions were identified by a state-of-the-science review conducted in 2008 (Vilks, 2009).

Sorption experiments to address these gaps and to develop an understanding of sorption processes in Na-Ca-Cl brine solutions within Canadian sedimentary rocks (and bentonite) were initiated in 2009 (Vilks et al., 2011). Protocols for batch sorption tests with Na-Ca-Cl brine solutions were developed, including: 1) guidelines for experimental configurations; 2) solid/liquid ratios; 3) phase separation methods; and 4) sorption time scales. Sorption of elements Sr (as an analogue to Ra), Cu, Ni, Eu (as an analogue to trivalent actinides), and U on bentonite, shale and limestone was tested in Na-Ca-Cl brine solutions with TDS values as high as 300 g/L. The results demonstrated that Sr(II) will not sorb, but that sorption of Cu(II), Ni(II), Eu(III), and U(VI) to bentonite, shale and limestone in brine solutions is measurable (Vilks et al., 2011). The formation of complexes with carbonate reduced the sorption of Eu(III) and U(VI). Preliminary sorption coefficients for these elements in sedimentary rock were recommended.

The development of a Canadian sorption database was initiated in 2010. The initial stages involved a review of the open literature and international sorption databases to find available data relevant to Canadian sedimentary rocks (shale and limestone) and bentonite for the elements Am, As, Bi, C, Cu, Mo, Nb, Np, Pa, Pb, Pd, Pu, Ra, Se, Sn, Tc, Th, U and Zr, in a setting that includes Na-Ca-Cl brine solutions at near neutral pH. Redox conditions were factored for those elements that are redox sensitive. Experimental sorption coefficients of Cu (II) and U(VI) (Vilks et al. 2011) were recommended for these two elements. Chemical analogue elements were used to fill data gaps. Experimental sorption data of Sr(II), Ni(II), Eu(III) and U(VI) measured on bentonite, shale and limestone in brine solutions (Vilks et al., 2011) were used as chemical analogues. A set of sorption values was recommended for bentonite, shale and limestone (Vilks, 2011). The recommended sorption values are intended as a starting point for the development of a Canadian sorption database for sedimentary rocks.

In 2011, a two-year research program was initiated in collaboration with Atomic Energy of Canada Limited (AECL) to further develop the sorption database for Canadian sedimentary rocks (and bentonite) in highly saline solutions. The work program includes: 1) batch sorption tests to determine sorption coefficients and improve the understanding of sorption processes, and 2) mass transport studies to better define the effect of sorption on mass transport. In addition, sorption modelling will be performed to illustrate and understand the effects of key variables, such as pH, Eh and carbonate concentration, on sorption properties, and to extrapolate sorption values to new solution conditions.

Batch sorption tests are currently being conducted for the elements U, Zr, Pb, Cu and Se and follow developed experimental protocols (Vilks et al., 2011). The batch sorption tests will address the following aspects: 1) effect of pH on sorption; 2) sorption kinetics (to evaluate sorption behaviour as a function of time for up to 6 months); 3) desorption (to evaluate the reversibility of sorption reactions in response to the dilution of their concentration in solution); and 4) microbiology (to determine whether or not microbes could have any influence on laboratory sorption results).

The mass transport experiments focus on diffusive and advective transport through unfractured Ordovician shale core samples. Two mass transport tests are being performed: 1) diffusion tests with sorbing tracers performed for a relatively long time frame, with breakthrough curves or diffusion profiles being used to characterize diffusive transport; and 2) advective transport through a rock matrix using the High Pressure Radioisotope Migration (HPRM) apparatus described by Vilks et al. (2011).

The recommended sorption dataset (Vilks, 2011) will be further assessed and updated on the basis of the new results (batch and mass transport tests), sorption modelling, and any new values published in the literature.

4.2.4 Microbiology Processes and Methods

NWMO microbiology research in support of the development of a DGR for used nuclear fuel investigates the role of microorganisms in both the near- and far-field. The near-field program examines activity and survivability in the engineered barrier system (EBS), while the far-field program examines the microbiology of the host rock. The objective of these research programs is to identify design provisions that may be necessary to suppress microbial activity in the repository and to prepare for site characterization activities.

4.2.4.1 Near-field Microbiology

A state-of-knowledge review regarding near-field microbiological considerations relevant to a DGR for used nuclear is currently under preparation by researchers at both Ryerson University and the University of Saskatchewan. The report will draw on peer-reviewed scientific literature, as well as publicly available reports from nuclear waste management programs both internationally and in Canada, in order to evaluate near-field microbiological considerations for repository engineering and safety assessment of a deep geological repository. The specific objectives of the review are to: 1) review research (both experimental and modelling based) on microbial activity and survivability in a deep geological repository for used nuclear fuel; 2) review potential Canadian host rock and repository design options and discuss the potential implications of microbial activity on those designs; and 3) review findings of long-term EBS performance in relation to evolving conditions in the repository. The goal is to identify any gaps in knowledge and understanding of microbial processes in a deep geological environment that could affect the long-term performance of the EBS. On the basis of the review, an approach for the development of both an investigation strategy and a near-field microbiology technical program, to be implemented in support of APM, will be proposed in 2012.

In June 2011, NWMO became a partner in the Hydrogen Transfer (HT) experiment in the Mont Terri Underground Rock Laboratory. The HT experiment aims to evaluate diffusion of hydrogen in the Opalinus Clay, measure hydrogen consumption processes in the experimental borehole, and if possible, identify the role of microbial activity on these processes. The experiment involves the release of H_2 in a gas circulation experiment in an experimental borehole. The project will continue until June 2013.

4.2.4.2 Far-field Microbiology

In 2011, NWMO published a state-of-knowledge review regarding far-field microbiological considerations relevant to a DGR for used nuclear fuel by the University of Toronto (Sherwood Lollar, 2011). The presence, diversity and activity of indigenous microbial populations in the far-field is controlled by a number of factors, including: geologic (physical) and chemical (including mineralogical) properties of the host rock; transport properties of the host rock; geochemistry of the associated groundwater; hydrogeologic properties; and the geologic and geochemical history and evolution of the site. The report recognizes that indigenous microbes exist in a broad range of geologic environments and that it cannot *a priori* be assumed that a subsurface geologic environment will be sterile. The report outlines a preliminary approach for microbial analyses that should be conducted as part of detailed site characterization activities, and emphasizes that microbiological far-field investigations should incorporate techniques that eliminate, to the degree possible, any contamination due to sampling/drilling, and should also control for contamination by characterizing not only the indigenous geochemistry and microbiology, but also the geochemical and microbiological properties of any potential contaminant end-members (e.g., drill water).

In 2011, NWMO continued its involvement in the Microbial Activity (MA) experiment at the Mont Terri Underground Research Laboratory. The results of the MA experiment, summarized in Stroes-Gascoyne et al. (2011), indicate that drilling-related disturbances, particularly contamination with organic matter, fostered a temporary bloom of anaerobic microbes, including NO_3-, Fe- and SO_4- reducers and methanogens in an experimental borehole. However, Wersin et al. (2011) concluded that, due to the large buffering capacity and diffusion-dominated nature of the clays, the effects of drilling and excavation disturbances will be temporary and spatially limited. Similarly, Sherwood Lollar (2011) concluded that hydrology, geochemistry, and resident microbial populations may be sensitive to changes or perturbations in the system, but that many systems possess a geochemical buffering capacity to counter the effects of perturbations. To further evaluate this hypothesis, NWMO will continue its participation in the MA experiments at Mont Terri in 2012. Planned experiments will evaluate the effects of geomechanical and geochemical perturbations associated with the excavated damage zone of a borehole or gallery, which can provide favourable conditions for the growth of microbes, either indigenous or extraneous (i.e., introduced when more space and water become available).

4.2.5 Geomechanics Activities

The NWMO geomechanical work program concentrates on near-field research, where the near-field is defined as the rock mass in the immediate vicinity of any underground openings. The areas of research can be divided into two branches: 1) characterization of rock properties at field and laboratory scales, and 2) numerical modelling of the rock mass behavior. The objectives of the geomechanics technical activities are to: 1) provide support for preliminary field investigations associated with siting and feasibility studies; 2) conduct detailed site characterization activities and investigations of rock mass response in either sedimentary or crystalline rock; and 3) assemble supporting arguments and evidence of long-term stability for use in a DGR safety case.

A key aspect of this preparatory work is to assess thermo-hydro-mechanical (THM) processes in different rock masses, which is required for the design, construction, operation and performance/safety assessments of underground used nuclear fuel repositories and other civil and environmental engineering works. In order to assess the extent to which the properties of the host rock will be altered by THM processes associated with the used fuel, reliable rock mechanical data is required for modelling and engineering design of the underground openings at various scales. An experimental work program at the University of Toronto was on-going in 2011 to characterize THM coupled processes and properties (Section 4.2.5.1). In 2011, two new geomechanical research programs were initiated. The Synthetic Rock Mass Program (Section 4.2.5.2) is a collaborative effort to establish an improved method for the prediction of rock mass behaviour, and the effects of anisotropy and scaling on the measured hydro-mechanical properties of rock are being investigated in a new research program at McGill University (Section 4.2.5.3). Understanding of the presence and distribution of fractures in intact rock masses, and the effects of fractures on the excavated damage zone (EDZ) were also examined in 2011 (Section 4.2.5.4).

4.2.5.1 Coupled Thermo-Hydro-Mechanical (THM) processes in sedimentary rocks

The objective of the University of Toronto THM experimental work program is to test the coupled thermo-hydro-mechanical properties of sedimentary rocks that are representative of those found in Canadian deep sedimentary basins. The first phase was completed in 2010, and the second phase of the experimental study was initiated in 2011. The second phase consists of three groups of experiments: 1) determination of the physical properties of Lindsay limestone specimens (cored at St. Mary's Cement quarry in Bowmanville, Figure 4.1); 2) uniaxial compressive strength (UCS) tests on dry and re-saturated (i.e., in the laboratory) Lindsay limestone samples, tested at ambient temperature and thermally treated at 50°C, 100°C and 150°C (Figure 4.2); and 3) utilization of a geophysical imaging Hoek-type cell capable of performing THM triaxial compressive experiments loaded within a servo-controlled loading machine.

Coupled THM experiments were conducted under two different stress regimes within the geophysical imaging cell. First, the specimens were heated to targeted temperature under a constant confining stress of 12.5 MPa, and under restricted axial strain control mode. Once the targeted temperature was reached, deviatoric stress was increased under constant temperature and confining pressure until sample failure. The results from these thermo-hydro-mechanical experiments suggest that the specimens tested at 100°C show a higher average triaxial compressive failure strength of 132 MPa, compared to the rest of the specimens tested at room temperature (103 MPa), at 50°C (92 MPa) and at 150°C (125.5 MPa).

Permeability values measured under a hydrostatic stress of ~12.5 MPa, at room temperature, for all heat-treated specimens show a consistent trend: permeability for respective target temperatures show a reduction proportional to the amount of thermal treatment experienced. The measured permeability values range from about 1E-18 to 1E-19 m^2 between the individual samples. This observation confirms the fact that the initial closure of micro-cracks and compaction occurs in association with increased thermal pressurization (heating under axial displacement control mode), which decreases the permeability of the rock. As deviatoric stresses reach beyond the onset of the crack dilation threshold, permeability increases. In the study, a self-consistent relationship among strength, deformation, wave velocities, elastic constants and permeability during the various stages of the THM experiments for Lindsay limestone specimens was observed, despite its heterogeneous and anisotropic nature. A full report describing the two-year research work will be released in 2012.

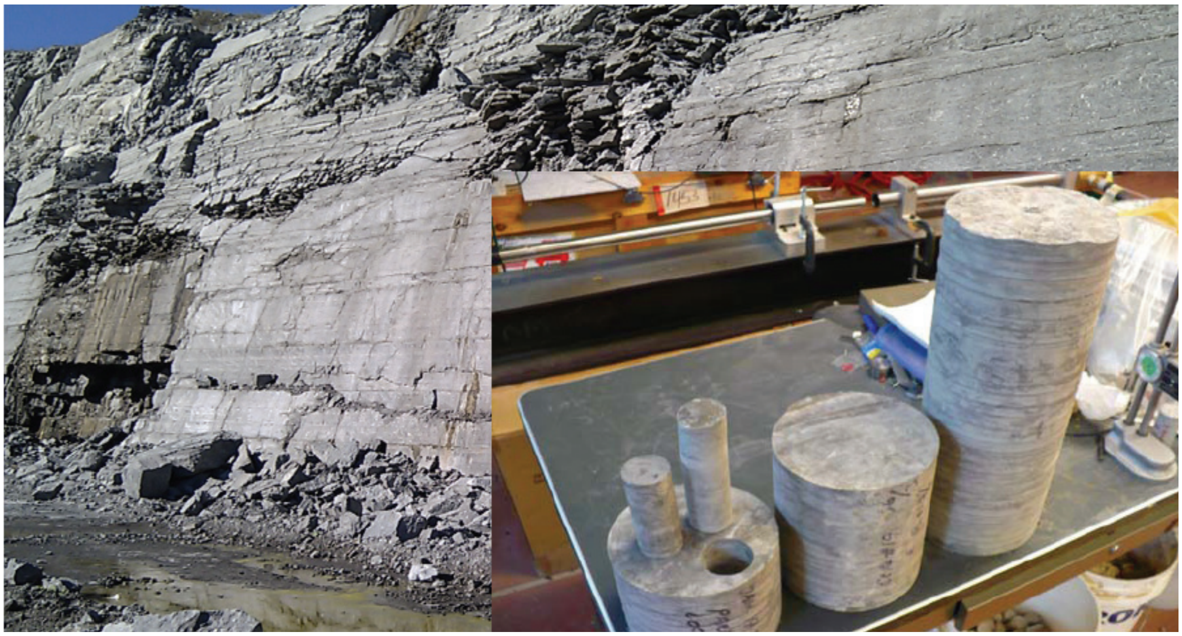

Figure 4.1: Samples for THM Properties Collected at St Mary's Cement Quarry in Bowmanville, Ontario

Experimental research to advance testing of sedimentary rocks in such complex THM environments continues in 2012. As part of this work program, quality and test plans are developed and documented for the experiments conducted at the facility. This will also include an inter-laboratory comparison between McGill, Queen's and University of Toronto to assess potential laboratory artefacts. The laboratory experiments, under varying THM conditions, include triaxial (biaxial) and true triaxial tests to simulate the stress state in a tunnel wall during the excavation stage and the development of Excavation Damage Zone (EDZ). During the experiments, acoustic emission (AE) and ultrasonic velocity data is collected, which will be used to assess the damage in the rock samples and to validate numerical models. The work complements and contributes to the other on-going geomechanical activities, such as the Synthetic Rock Mass (Section 4.2.5.2), anisotropy and scaling (Section 4.2.5.3), and assessment of the EDZ (Section 4.2.5.4) programs.

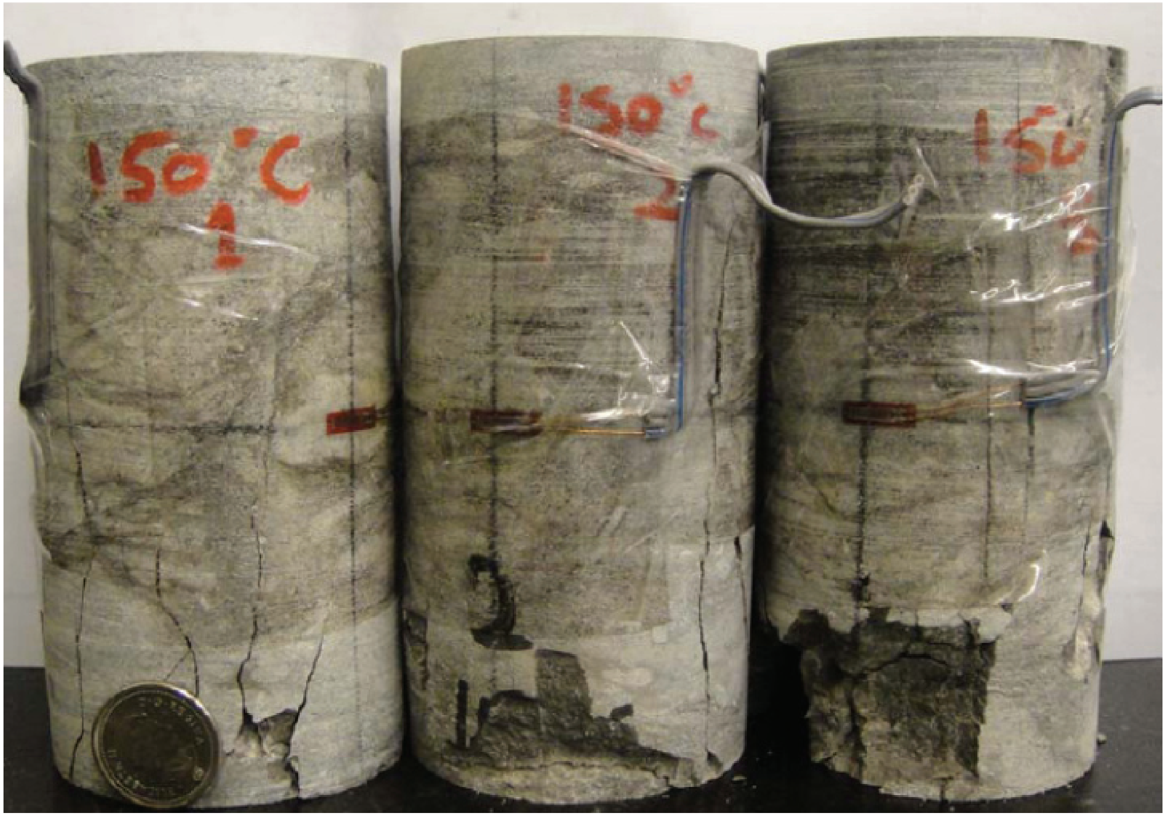

Figure 4.2: Specimens Treated at 150°C, Following Completion of the Uniaxial Compressive Strength Test

4.2.5.2 Synthetic Rock Mass Program

Over the past ten years there have been significant advances in geomechanical modelling of rock masses. These advances have developed from a general realization and acceptance that the failure of rock has two components: 1) fracture of intact rock, and 2) movement along existing discrete fractures. Traditional continuum and discontinuum modelling methods for mechanical behaviour of rock do not treat these components as separate processes affecting the same elemental volume of rock, but rather simply combine them using a descriptive constitutive model to simulate the failure process through intact rock zones or along pre-defined failure surfaces. The purpose of the Synthetic Rock Mass (SRM) program is to improve the prediction of the response of rock masses to facilitate the design and excavation of a deep geologic repository. SRM modelling takes a different approach, using Discrete Element logic to capture the failure of the individual components. In this formulation, there is no pre-defined failure surface for discontinuum failure, nor any complex constitutive model for intact rock damage.

While the SRM modelling uses the most advanced tools available today, the methodology has not been verified. In addition, the mining problems that are being addressed by the SRM are not necessarily applicable to nuclear waste repositories. Moreover, virtually all investigations of this type have been driven by studies related to granitoid rock masses. There is a need to develop this work for applications in sedimentary rock as well, particularly for limestones and shales.

The SRM response of sedimentary rock needs to be simulated at several scales (Figure 4.3) ranging from the grain scale (crystals or grains bounded by grain boundaries), the sample or lamination scale (including bedding or inherent layering), the excavation scale (interaction of intact damage and pre-existing planes of weakness), and finally, the larger (regional) scale – interaction of long-term fracture development with geological structure(s) over numerous (glacially induced) stress cycles subject to hydro-mechanical and thermo-mechanical influences.

The SRM research at NWMO is a multi-year work program that started in 2011 in order to collaboratively establish an improved method for the prediction of rock mass behaviour in the context of the design and excavation of underground openings. The program will be conducted in collaboration with SKB, Queen's University and the University of Alberta. The work program advances conventional techniques by simulating rock mass response at a variety of length scales, involving the application of Discrete Element logic in established numerical codes such as UDEC and PFC (Itasca, 2006, 2008a, 2008b). The SRM research will further improve the understanding of the rock mass response in fractured bedrock settings, while developing applied and practical approaches for DGR design. The results of the research will advance our understanding of rock mass behaviour, support development of reference engineering designs and illustrative safety cases, and enhance our confidence in predicting both the short- and long-term performance of a DGR.

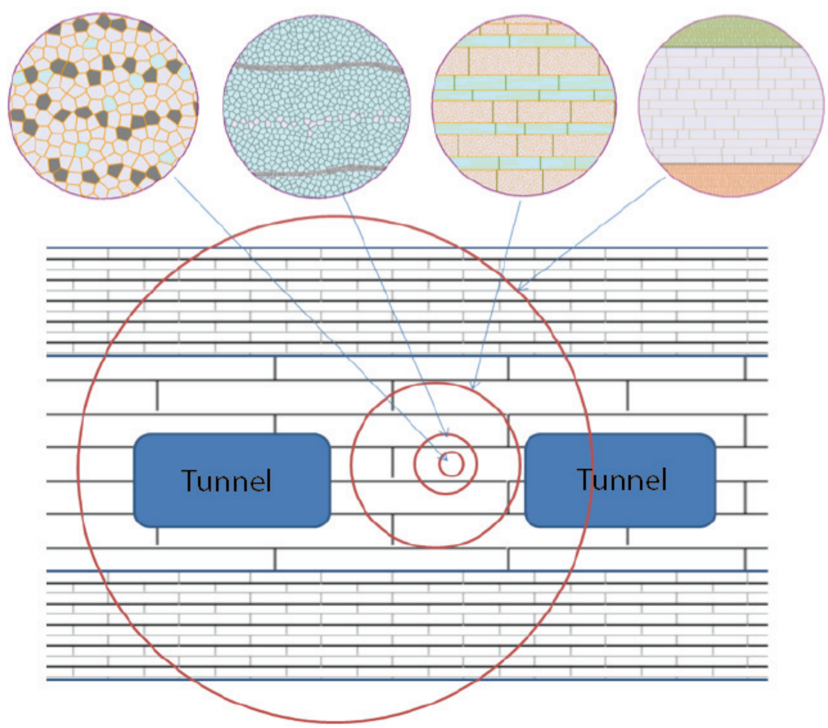

Figure 4.3: Illustration Showing the Transition from Intact to a Bedded-jointed Rock Mass with Increasing Sample Size

4.2.5.3 <u>Anisotropy and Scaling of Coupled Hydro-mechanical Properties of Rock</u>

A research program has been initiated at McGill University to extend past and on-going experimental research programs examining the effects of anisotropy and scaling on measured hydro-mechanical properties. The planned tests will employ larger-scale specimens (measuring from 75 mm diameter and 150 mm in length up to 150 mm in diameter and 300 mm in length). This range of sample sizes is intended to adequately capture the role of internal fabric (i.e., anisotropy) on the representative properties of limestone as they relate to physical, mechanical (both deformability and failure) and fluid transport behaviour.

The research program began in the summer of 2011 with the collection of samples (as rock blocks) from the St. Mary's Cement quarry in Bowmanville. Cubical and cylindrical samples were then cut and cored from the blocks, oriented both along the identifiable planes of stratification and oblique to identifiable planes of stratification (Figure 4.4). The samples were then catalogued and instrumented for mechanical testing, such as Hoek-Cell tests, plug tests, and Brazilian tests, for the assessment of the deformability and failure characteristics of the limestone. Approximately 100 cores were prepared for the tests from the collected rock blocks and the testing will take place in 2012.

Figure 4.4: Samples Cored and Prepared Parallel and Perpendicular to Bedding Planes

4.2.5.4 <u>Assessment of Excavation Damage Zone (EDZ)</u>

In the APM program, the strategy for assessing the role of the EDZ in brittle sedimentary rocks in the DGR concept is to: 1) gain an understanding of the role of the EDZ in the possible creation of discrete pathways for mass transport along the excavated and backfilled openings in the rock; 2) minimize the extent of damage to the host and surrounding rock mass through appropriate excavation methods; 3) minimize the potential for large EDZ by optimizing geometry of excavated openings, based on knowledge of the stress state and influence of cut-off excavation on EDZ re-distribution; and 4) evaluate and develop sealing methods.

In 2011, this research was mainly focused on investigating existing excavations in limestone, strength testing data on limestone, and using continuum models to evaluate the dimensions of

EDZs. Research on the development of a new geomechanics classification system, specifically for carbonate or argillaceous rock, is also in progress. The research study will also expand to other sedimentary rock types, such as shale, in 2012, in an effort to understand and anticipate rock mass behavior that may be encountered at both the repository level and in the access shafts in sedimentary environments.

Experience from existing limestone excavations indicates that limestone is a strong, brittle material. Observation of the Quintner limestone at the 500 m level, at the Gonzen iron mine in Sargans, Switzerland, shows that spalling is localized at stress concentrators, such as corners of square openings (Figure 4.5). This is in agreement with laboratory test results, which typically show that fine-grained limestone, such as the Quintner from Switzerland or the Cobourg from Canada, has proportionally similar strength thresholds as a percentage of the ultimate strength (Figure 4.6). These in-situ observations can be utilized to improve predictive numerical models, which in turn, can be used to determine likely dimensions of the EDZ.

Figure 4.5: (a) Excavation Damage (spalling) of Quintner Limestones, (b) Close up of (a)

Numerical modelling allows for a better understanding of the typical dimensions of excavation damage zones. Building on early research on EDZs at Queens University, in which a methodology to identify the dimensions of EDZs from numerical models was established (Perras et al., 2010), and using laboratory test results from the Cobourg Formation limestone (INTERA, 2011), a series of models were computed to determine the smallest, average, and largest HDZ Highly Damaged Zone (HDZ), inner Excavation Damage Zone (EDZ_i) and the outer Excavation Damage Zone (EDZ_o). Each damage zone was represented by a cumulative distribution function (CDF), as shown in Figure 4.7. The cumulative distribution function can be used to demonstrate the level of confidence in the dimensions of each damage zone. The CDF can be used for design purposes to determine the depth to which a cut-off is required to be excavated around a repository opening in order to limit flow along the EDZ.

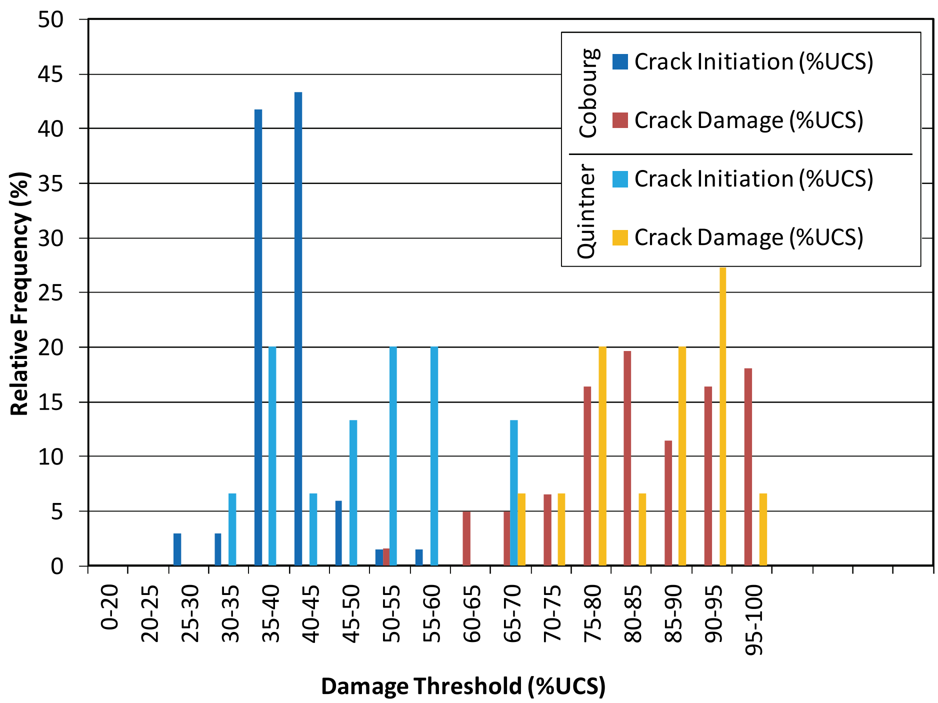

Figure 4.6: Strength Thresholds for the Quintner and Cobourg Limestones

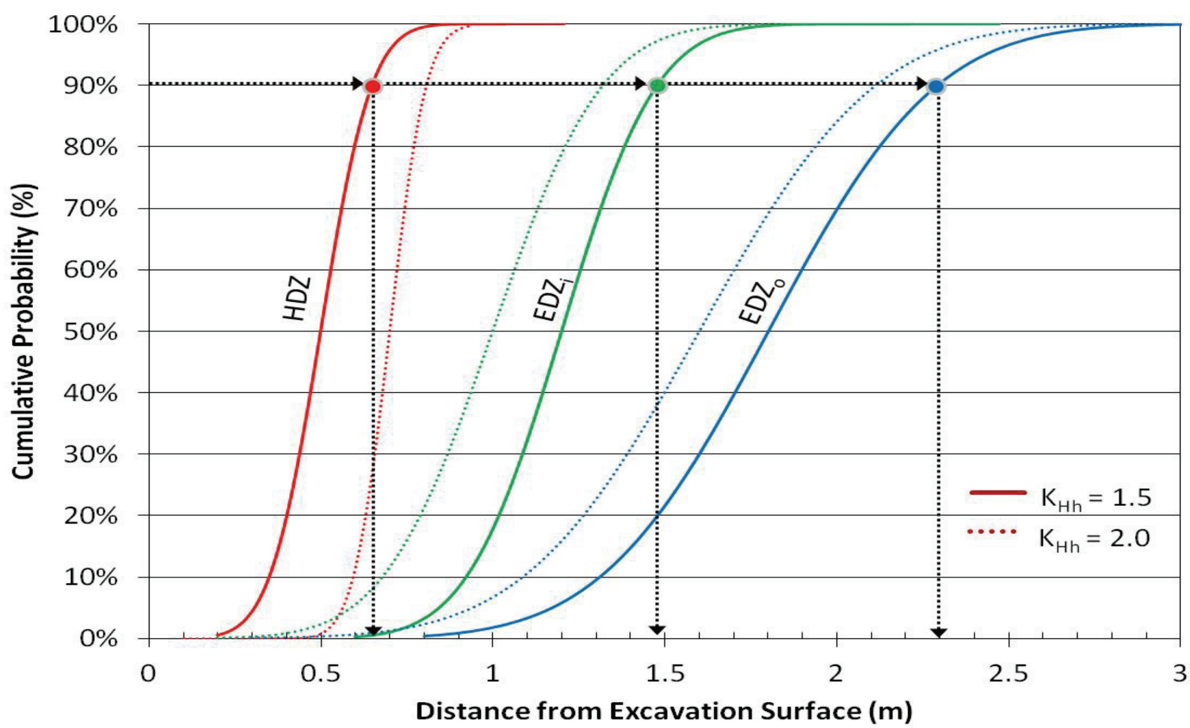

Figure 4.7: Cumulative Probability Distribution for Limestone Showing the EDZs for Both a Horizontal Stress Ratio of 1.5 and 2; the Arrows Indicate the Dimensions of the EDZs with 90% Confidence

Further research will be conducted in 2012 to refine the CDF method to ensure that the rock mass behavior is captured correctly in the process. The research in 2012 will also investigate the influences on fracture growth in laboratory specimens, and the identification of the EDZ around existing excavations using geophysical methods. Numerical modelling at the excavation scale will continue, and, specifically, will examine excavation intersections and cut-off shapes and how these influence the EDZ.

4.2.6 Seismicity

The seismic design of a DGR requires an understanding of anticipated ground shaking at repository depth. In 2011, NWMO activities continued to support seismic monitoring by the Canadian Hazards Information Service (CHIS) of Natural Resources Canada (NRC) and assessment of earthquake impacts on underground structures by MIRARCO at Laurentian University, as described in the following sections.

4.2.6.1 <u>Seismic Monitoring of the Canadian Shield</u>

NWMO continues to gain knowledge on the seismic characteristics of low seismicity regions of the Canadian Shield in collaboration with the CHIS of the NRC monitoring program. The purpose of NWMO participation is to monitor the low levels of background seismicity in the stable cratonic region of the Canadian Shield. The CHIS monitoring network consists of 18 seismograph stations spreading from Pinawa, Manitoba, in the west, to Chalk River, Ontario, in the east. All stations record real-time, continuous, digital data, which are transmitted by satellite to the NRC data laboratory in Ottawa. The results of the 2010 seismic monitoring program were published in 2011 (Hayek et al. 2011). A total of 118 events were recorded in 2010, ranging in magnitude from 0.7 mN to 3.2 mN (Figure 4.8), and the results are presented in detail in McKelvie et al. (2011). The events (118) located in 2010 are comparable with recorded events in 2009 (82 events), 2008 (114 events), 2007 (68 events) and 2006 (83 events). The seismic monitoring data from 2011 is being compiled and will be published in 2012.

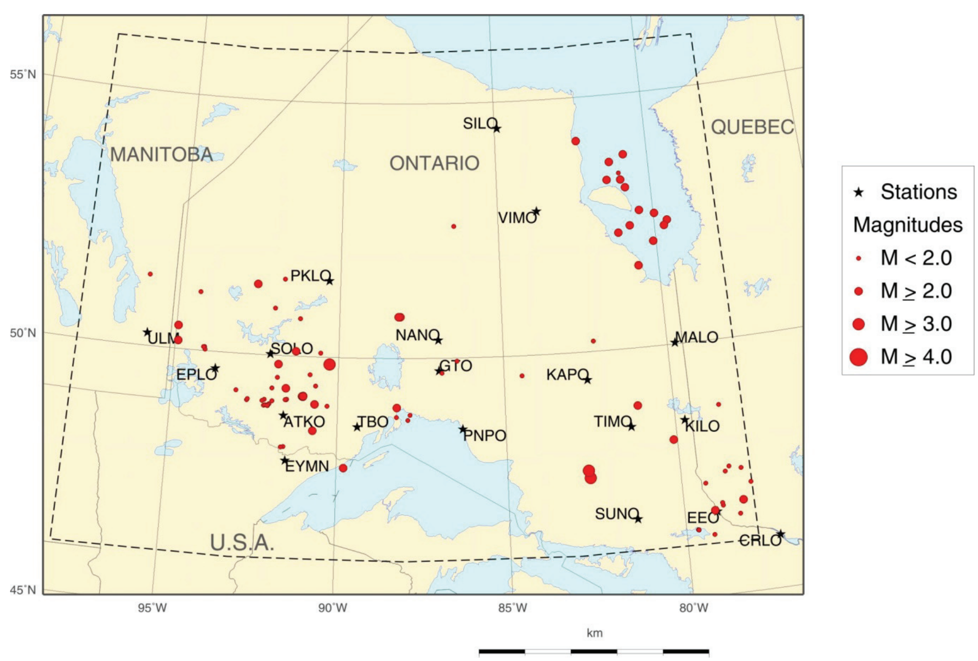

Figure 4.8: Magnitudes (M) of 2010 Seismic Events in Northern Ontario; Dashed Line Depicts the Study Area

4.2.6.2 Earthquake Impacts on Underground Repositories

MIRARCO at Laurentian University conducted a literature review on the current state-of-practice in the area of fault-slip seismic events and their potential impacts to underground repositories for nuclear waste located in crystalline rock. The impact of an earthquake on the slip on fractures in a repository can be divided into: permanent deformation, accumulated deformation, and temporary dynamic loading or strain. The key set of factors for evaluating the impact of earthquakes on a waste container (Figure 4.9) are: the magnitude and frequency (rate of occurrence) of earthquakes, the distance of the earthquake from the fracture intersecting a container, the size and aspect ratio of the fracture intersecting the deposition hole, and the orientation of the fractures.

In general, there is a magnitude-distance relationship that indicates a rapid decay in body-wave seismic energy due to geometric spreading. Natural, or induced, earthquakes produce little damage to underground openings outside the immediate epicentral area (far-field). Within the epicentral area (near-field), damage due to shaking, spalling, rock falls, and water influx are possible. Similarly, slip of fractures is also unlikely outside the immediate epicentral area. The epicentral area is typically less than 100 m for a moment magnitude 4.0 event to less than 100 km for a moment magnitude 8.0 event.

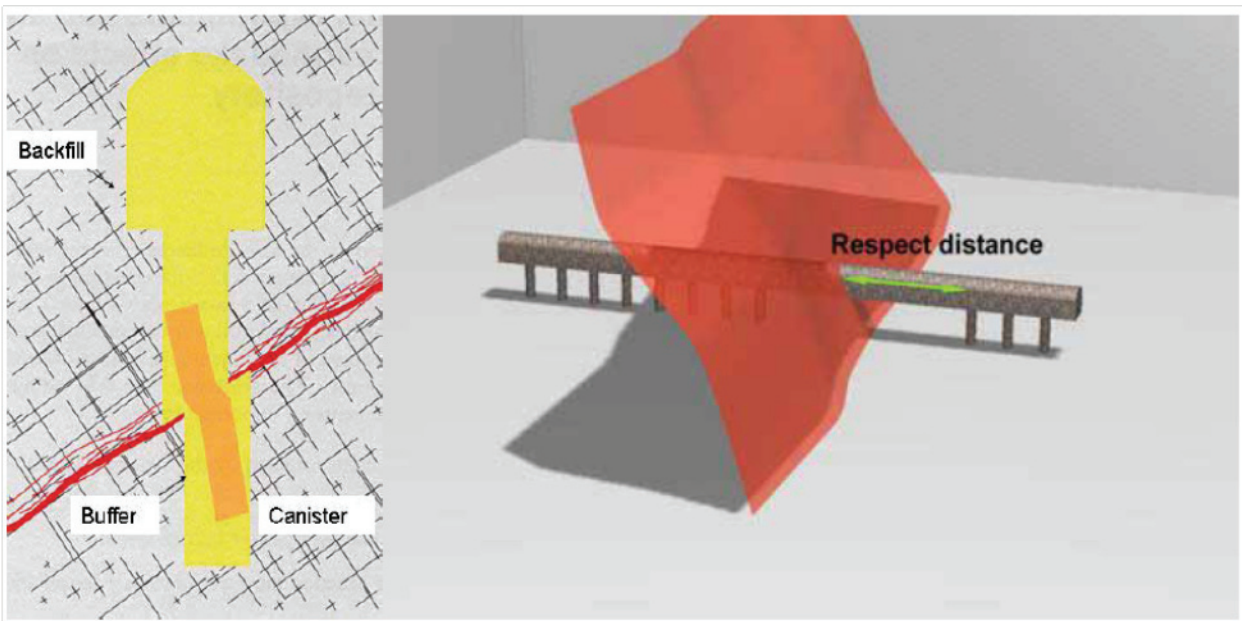

Figure 4.9: Concept View of the Impact of a Fault-slip Event on a Waste Container in a Repository

4.2.6.3 Paleoseismicity and Neotectonics

NWMO continues to develop its capabilities and understanding in the field of paleoseismicity and neotectonics as they pertain to geosphere predictability and resilience to perturbations. A technical report entitled "Review of Paleoseismological Methods for Seismic Hazard Assessment and Their Applicability to Central and Eastern Canada", written by Dr. John Sims, will be published in 2012. Dr. Sims has acted as a senior supervisory research geologist at the US Geological Survey and has been involved in neotectonic studies in California, Oregon and in the New Madrid seismic zone. The report describes both proven and promising paleoseismological features, as well as discussion of the various methods used to study such features. The applicability of the study of these features and the methods used to identify them are also discussed in the context of both the Quaternary geological and seismological settings of Ontario and Saskatchewan. This technical report provides background information required for the successful implementation of future paleoseismological work, which is a necessary component of the APM siting program.

4.3 LONG-TERM GEOSPHERE STABILITY

4.3.1 Glaciation

Over the life of a deep geologic repository, the strongest perturbation to the repository and geosphere system will be future glacial cycles. During glaciation, upwards of 3 km of ice will override the repository site, and stress from the ice sheet will be transmitted into the geosphere to both the rock mass and the fluids within. Given the strong perturbation associated with glaciation, the NWMO is refining the numerical tools to investigate the impact of long-term climate change on the performance and safety case of a DGR. Potential impacts of glacial cycles on a DGR include: increased stress at repository depth caused by glacial loading; penetration of permafrost to repository depth; recharge of oxygenated glacial melt water to repository depth; and, the generation of seismic events and faulting induced by glacial rebound following ice-sheet retreat.

4.3.1.1 Glacial Systems Model

An important element in assessing the potential impact of glaciation on a DGR is the ability to adequately predict the surface boundary conditions during glacial cycles. These boundary conditions include permafrost extent and depth, ice-sheet properties (extent, thickness and kinematics), ice-sheet hydrology, as well as other attributes. For NWMO's glaciation case studies, these boundary conditions have been defined based on predictions from the University of Toronto's Glacial Systems Model (GSM) (Peltier, 2006). The GSM is a state-of-the-art model of continental scale ice-sheet evolution that has been enhanced to enable calibration using a Bayesian methodology. This methodology allows the model to reconcile a large body of observational constraints governing ice advances and retreats over the North American continent during the Late Quaternary Period of Earth history. The objectives of this research are to maintain and further develop modelling capabilities in the area of Glacial Systems Modelling; maintain and expand Canadian expertise in this area; and promote knowledge transfer through the involvement of Postdoctoral candidates and graduate students.

There are several aspects of the GSM that require further development to improve predictions of glacial boundary conditions and, consequently, to improve predictions of surface boundary conditions employed in illustrative simulations supporting the DGR safety case. In the present model, which is based upon the "shallow ice approximation", longitudinal stresses are entirely neglected. Furthermore, the representation of the interaction of ice streams with the ocean, into which they often discharge, is inadequately treated. Because ice streams drain the interior of the ice sheet, and thereby control its thickness history, especially insofar as rapid climate change related processes are concerned, the accurate description of such processes is critical to the success of the model. The purpose of the University of Toronto work program is to improve and maintain the GSM. This will be achieved by improving the implementation of the physics describing the flow of ice over the landscape. In addition to the improvements to the code, simulations to define the distribution and impact of the 3D stress field that will develop in front of an advancing and retreating ice sheet are currently being undertaken. The 3D stress distribution, along with updated glaciation boundary conditions will be provided in a technical report. The 3D stress field can be used to help investigate the impact of shear stresses on the geosphere and repository system.

4.3.1.2 Testing of Hydro-Mechanical Enhancement of FRAC3DVS-OPG

In a fractured crystalline environment, glacial loading could cause changes to the hydraulic properties of the rock mass in both the unfractured rock matrix and along the fracture planes. These hydraulic changes can potentially alter groundwater flow patterns, thereby affecting mass transport. The effects of glacial loading are not limited to the rock mass directly under the ice; a change in the stress ahead of the glacial front may also occur (due to the Poisson effect).

FRAC3DVS-OPG is a numerical modelling code used to simulate groundwater flow and solute transport. Hydro-mechanical coupling in FRAC3DVS-OPG is limited to purely vertical strain with lateral constraints (Guvanasen, 2007). In order to better address the issue of thermo-hydro-mechanical coupling (see Section 4.2.5.1), a new module has been developed and incorporated into the FRAC3DVS-OPG code. The thermo-hydro-mechanical coupling approach is based on the extended Biot's formulation for non-isothermal consolidation in poroelastic materials. The module has been verified against known analytical solutions for isothermal and non-isothermal consolidation. Fractures are incorporated into the module as stress-dependent composite material properties.

Following the development of the thermo-hydro-mechanical module, a benchmarking and verification study was undertaken to investigate methods for complex geometric representations, using a staged approach, as a means to test the module. The testing of the module involved a series of simulations with increasing spatial dimensionality and complexity, including 2- and 3-Dimensional simulations of homogeneous and heterogeneous geospheres. The representation of an ice-sheet was also investigated because a key goal of creating the 3D THM module for FRAC3DVS-OPG was to assess the impact of glacial advances and retreats on fluid dynamics within the rock mass. The 3D THM module for FRAC3DVS-OPG was also tested against the existing 1D vertical HM loading module in FRAC3DVS-OPG. Results of the THM comparison will be summarized in a Technical Memorandum in 2012.

4.3.1.3 Greenland Analogue Project (GAP)

In collaboration with SKB and POSIVA, NWMO continued its involvement in the Greenland Analogue Project (GAP) in 2011. The objective of this four-year project (2009-2012) is to advance the understanding of processes associated with glaciation and their impact on the long-term performance of a DGR. The Greenland Analogue Project will improve knowledge and allow us to evaluate the impact of an ice sheet on groundwater chemistry at repository depth using the Greenland ice sheet as an analogue to future glaciations in North America.

Following an introductory field campaign in 2008 near Kangerlussuaq, Greenland, the GAP field program began in 2009 and included the successful initiation of ice sheet and geosphere/geochemistry studies. Through an extensive field and modelling program, the GAP is intent on assessing glacial hydrology, groundwater flow and groundwater composition (particularly redox conditions) at the base of a continental-scale ice sheet. Research conducted on the surface of the ice sheet has included the installation of GPS stations, ground-based radar and remote sensing of the study area, tracer tests conducted near the ice margin to look at water flow from the surface to the base of the ice sheet, and boreholes drilled through the ice to the ice bed. Samples have been collected as well from two boreholes drilled in the bedrock in front of the ice sheet to depths of up to 687 m in order to investigate groundwater geochemistry and microbiology at the glacial front.

In addition, a literature review of hydrogeology and hydrogeochemistry was completed (Wallroth et al., 2010). In 2011, a geochemical sampling program of surface water bodies, including a pingo, continued from previous years. A deep, inclined borehole (DHGAP04, ~687 m borehole length) was successfully drilled under the margin of the ice sheet (Figure 4.10) as well. The borehole was instrumented with a multi-level packer system below the permafrost to allow for the measurement of temperature, pressure, electrical conductivity, transmissivity of open fractures, and hydraulic head. Both core and water samples were collected from the deep borehole. A comprehensive report, detailing the results of the four-year field campaign and the associated data and modelling interpretations, is projected for 2014-2015.

Figure 4.10: Drill Rig at the GAP Field Site near Kangerlussuaq, Greenland

4.3.2 Evolution of Deep Groundwater Systems

NWMO continues to develop numerical methods to assess and quantify the robustness of site characterization data, as well as to predict the movement and distribution of groundwater over geologic timescales as relevant to a safety case. Numerical methods are used to assemble and test descriptive geosphere conceptual models developed through integration of multidisciplinary site characterization datasets. Through the application of illustrative scenarios, which can be used to test the internal consistency of conceptual models, numerical models are able to refine the understanding of groundwater system evolution and gain insight into geosphere processes, parameters and mechanisms in both crystalline Canadian Shield and sedimentary basin environments on repository safety time scales.

4.3.2.1 <u>Numerical Groundwater Modelling</u>

In order to develop readiness for detailed site characterization activities, as well as to advance the understanding of geosphere stability and its resilience to long-term perturbations, research is on-going to further develop and refine numerical modelling methods to investigate the evolution of deep groundwater systems. This program involves collaboration between the NWMO and the University of Waterloo, and has resulted in significant research contributions in the understanding of deep groundwater systems in both Canadian Shield and sedimentary basin settings (Normani et al., 2007; Sykes et al., 2011). An important component of understanding geosphere stability and resilience of the geosphere at depth to external perturbation is to constrain the uncertainty that can be associated with geosphere parameters required to construct numerical groundwater models. The performance measures used to illustrate the sensitivity of the conceptual model to geosphere uncertainty include mean life expectancies (MLEs), Peclet numbers and velocity ratios. For paleohydrogeologic scenarios, depth of penetration of glacial meltwater is also used as a performance measure (Figure 4.11). As a part of the current research program, the impact of geosphere parameters, such as salinity and rock mass and fracture permeability were investigated to determine their influence on groundwater migration and mass transport. The importance of honouring spatial and physical complexities and their impacts have also been investigated.

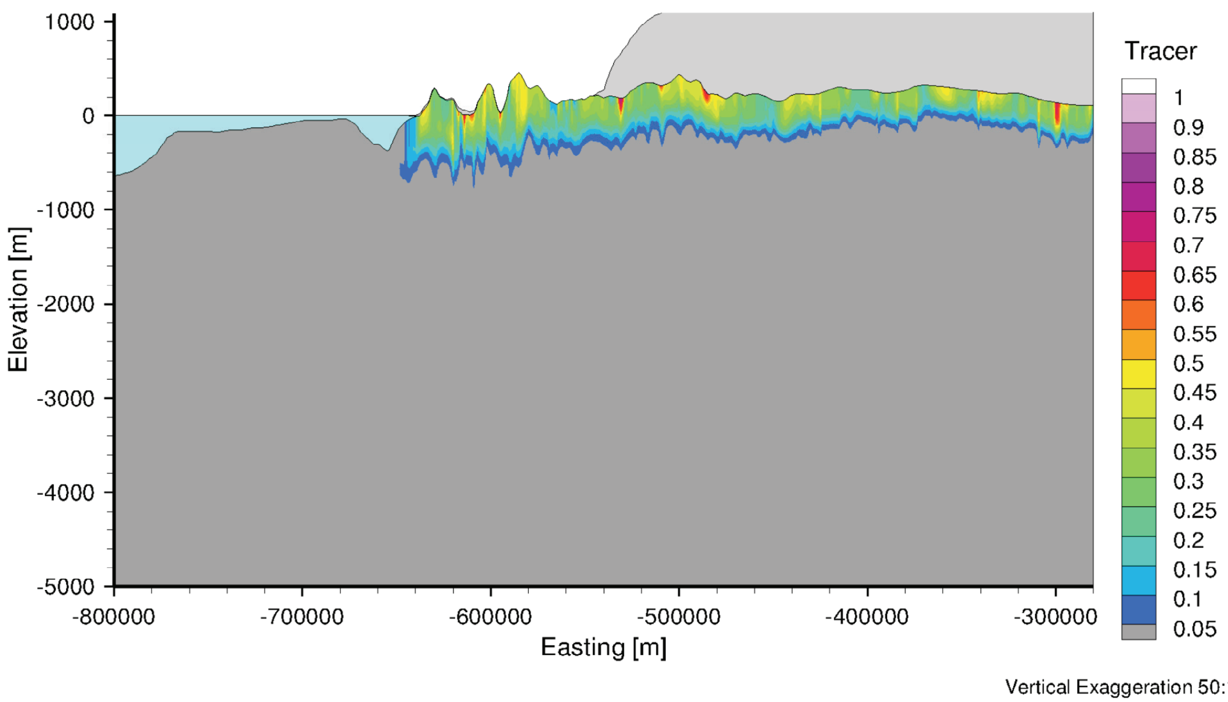

Figure 4.11: Depth of Penetration for a Tracer of Unit Concentration Recharging from Surface during Glaciation

In 2011, researchers at the University of Waterloo provided groundwater modelling support for the natural analogue project (see Section 4.2.1.1) investigating the natural tracer profiles and anomalous pressure distributions measured during site characterization for the Bruce L&ILW DGR. The objective of the support provided was to investigate the potential mechanisms for creating fluid pressure distributions in the Ordovician limestones and shales below hydrostatic levels through illustrative groundwater modelling. Glaciation and exhumation are being investigated as potential mechanisms for the under-pressured conditions.

In support of the Greenland Analogue Project (GAP), illustrative groundwater modelling was performed to support the on-going field activities. The objective of the GAP groundwater modelling is to investigate the impact of the representation and parameterization of the glacial boundary conditions in paleohydrogeologic groundwater models. The modelling performed in conjunction with the GAP project also investigated the impact of geosphere parameterization through alternate conceptualizations of the rock mass permeability.

In addition to the modelling support for the natural analogue project and the Greenland analogue project, the researchers at the University of Waterloo provided modelling support for both the Fourth Case Study and the Fifth Case Study. The objectives of the modelling in support of the Fourth Case Study and Fifth Case Study are to: 1) describe the current and long-term evolution of the hypothetical sedimentary rock groundwater system for purposes of illustrating the role and capacity of natural barrier systems to contain and isolate waste forms; and 2) illustrate attributes of the sedimentary and crystalline rock groundwater systems that contribute to an understanding of groundwater system stability and behaviour relevant to the development of a DGR safety case. The work in 2011 included performing MLE and tracer transport calculations to assist in the selection of repository locations.

4.3.2.2 Reactive Transport Modelling

Reactive transport modelling is one approach for assessing long-term geochemical stability in geological formations relevant to a DGR for used nuclear fuel. For example, reactive transport modelling can demonstrate 1) the degree to which dissolved oxygen may be attenuated in the recharge region of a DGR host rock; 2) how rock-water interaction (e.g., dissolution/precipitation, oxidation-reduction, aqueous complexation, ion exchange reactions) may cause groundwater salinity (density) to vary along flow paths; and 3) how diffusive transport of reactive solutes may evolve in the pore waters of low permeability geological formations.

MIN3P is a multicomponent reactive transport code that has been previously used to evaluate redox stability in crystalline rocks of the Canadian Shield (Spiessl et al., 2009). To simulate reactive transport in sedimentary rock environments, an enhanced version (MIN3P-NWMO) was developed (Bea et al., 2011). The code enhancements included: 1) calculation of ion activity correction in high ionic strength (up to 20 mol/L) solutions using the Harvie-Möller-Weare model, which is based on Pitzer equations; 2) calculation of fluid density for high ionic strength solutions; 3) one-dimensional hydromechanical coupling due to ice sheet loading; and, 4) coupled heat, fluid and solute transport. The new capabilities of MIN3P-NWMO were verified and tested for selected problems by comparing simulation results to analytical solutions and published results obtained by other established numerical models (Bea et al., 2011).

The enhanced MIN3P-NWMO code has been used to simulate flow and reactive transport in a hypothetical two-dimensional sedimentary basin (Figure Figure 4.12) subjected to a simplified glaciation scenario, consisting of a single cycle of ice sheet advance and retreat. The simulation results indicated that, during the period of deglaciation, Darcy velocity (specific discharge) increased in the shallow aquifers and deeper high-hydraulic conductivity units (e.g., sandstones) as a result of the infiltration of glacial meltwater below the warm-based glacier. However, these changes had a negligible effect on the fluid density distribution below depths of approximately 300 m. From a geochemical perspective, the simulation results revealed that dedolomitization occurred during the deglaciation period. However, dedolomitization was mainly restricted to the shallow aquifers and the net rates of dedolomitization were practically negligible for time scales on the order of 10,000 years. Although dissolution of halite was more significant locally (i.e., at the margins of the evaporite units), it was not as widespread as dedolomitization. Slight porosity enhancement was predicted as a result of halite dissolution in the evaporite unit. A preliminary sensitivity analysis of the geochemical stability in the hypothetical sedimentary basin, as a function of selected model processes and parameters, was also conducted (Bea et al., 2011). In general, the simulation results indicate a high degree of geochemical stability for this hypothetical basin.

In 2011, a new two-year research program was initiated in collaboration with both the University of British Columbia and the University of New Brunswick to develop a parallel processor version of MIN3P-NWMO (MIN3P-NWMO-P) that can perform reactive transport simulations more efficiently. MIN3P-NWMO-P will be able to utilize multiple processors simultaneously and can accommodate a higher degree of complexity and a finer discretization.

MIN3P-NWMO is currently being used to simulate the results of previously published tracer diffusion and in-situ disturbance experiments at the Mont Terri Underground Rock Laboratory (Wersin et al., 2008). The code is also being used to reproduce conceptual simulations of oxidizing, high-pH and high salinity perturbations for the Disturbances, Diffusion and Retention (DR-A) work program at Mont Terri (Soler, 2010).

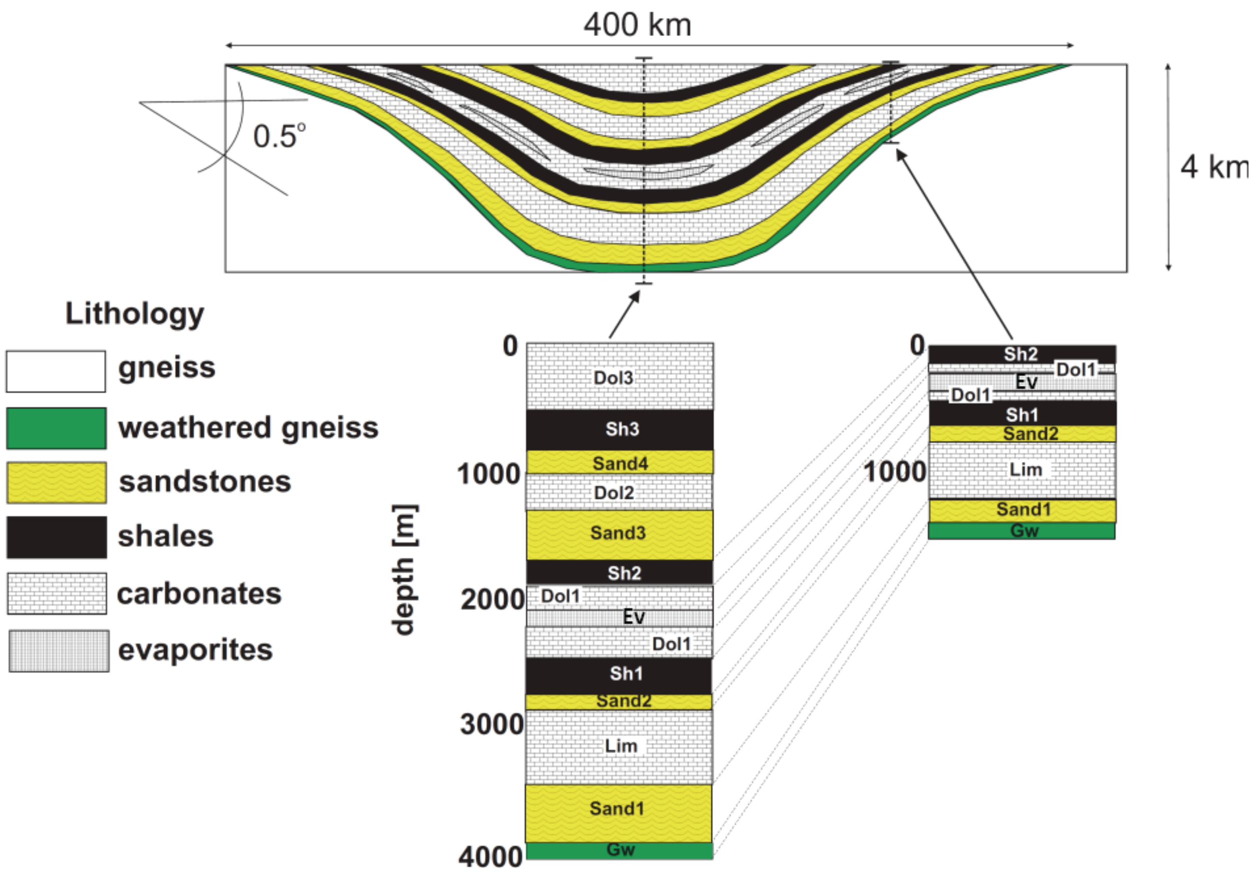

Figure 4.12: Hypothetical Two-dimensional Sedimentary Basin for Modelling of Flow and Reactive Transport during a Single Glacial Cycle Using MIN3P-NWMO

Reactive transport simulations with MIN3P-NWMO will be continued in 2012 using the in-situ, field-scale data from the DR-A experiment at the Mont Terri site, and the results will be compared with other reactive transport codes. Additional development of MIN3P-NWMO will be conducted to enhance model capabilities, focusing on simulation of diffusion in low permeability media. The enhanced code will be suitable for simulating diffusion-dominated migration through low permeability rocks, for both argillaceous rock and engineered barrier materials.

5. REPOSITORY SAFETY

5.1 ASSESSMENT CONTEXT

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

Garisto et al. (2009) provides a technical summary of information on the safety of a multi-barrier repository for used fuel. The report summarizes the key aspects of a deep geologic repository and explains why the repository concept is expected to be safe. The report is non-site-specific, considers alternative geologic settings – both Canadian Shield and sedimentary rock formations – and includes several design concepts. A list of the attributes that are typically considered relevant in the assessment of long-term safety are highlighted in Table 5.1.

Table 5.1: Typical Attributes Relevant To Long-Term Safety

- Repository depth provides passive isolation from human activities - Site low in natural resource potential - Multiple barrier repository system - Durable waste form - Robust container - Engineered clay seals - Low-permeability host rock - Low seismicity - Spatial extent and durability of host rock formation - Stable chemical and hydrogeological environment

5.2 MODEL AND DATA DEVELOPMENT

5.2.1 Wasteform Modelling

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

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

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

The 2011 program on UO_2 dissolution was carried out at the University of Western Ontario and included:

- Development of a preliminary model to predict the influence of redox conditions on the fuel corrosion rate (Beauregard, 2011);
- Determination of the influence of fuel composition on the reactivity of UO_2; and
- Determination of the kinetics of H_2O_2 reduction and decomposition on UO_2 surface.

A combination of electrochemical and open circuit corrosion measurements on UO_2 electrodes and surface analytical techniques were used in the investigations (Keech et al., 2011; Broczkowski et al., 2011). The tests were conducted with unirradiated 1.5%, 3% and 6% SIMFUELs, representing CANDU fuel burnups from about 210 to 800 MWh/kgU. SIMFUEL (simulated high-burnup UO_2-based fuel) is made by doping unirradiated natural UO_2 pellets with non-radioactive elements in order to replicate the chemical composition of used fuel, including the formation of so-called ε-particles – alloys of the fission products Mo, Ru, Tc, Pd and Rh. The influence of rare-earth doping was examined using gadolinium-doped UO_2. The results of the research undertaken at the University of Western Ontario are summarized in sections 5.2.1.1 through 5.2.1.3.

5.2.1.1 <u>Model to Predict the Influence of Redox Conditions on Fuel Corrosion</u>

A preliminary model of fuel corrosion was developed in 2011 using COMSOL. The aim of this model is to predict the corrosion rate of the fuel, in particular, the influence of redox conditions inside a failed used fuel container (fuel corrosion can only occur if water contacts the fuel; Beauregard 2011). The key oxidant promoting fuel dissolution in a failed container is H_2O_2 generated by the alpha-radiolysis of water (Eriksen et al., 2012).

The key reactions included in the preliminary model are: 1) radiolytic production of H_2O_2, 2) H_2O_2 reduction (on UO_2 and noble metal particles), 3) H_2 oxidation on noble metal particles, and, 4) H_2O_2 decomposition (the reaction of the resulting O_2 produced with UO_2 is not considered in this preliminary model). Radiolysis is assumed to occur evenly within a thin layer of solution at the fuel surface. A diffusion layer represents the separation between the fuel surface and the undisturbed source of H_2 (assumed to be formed by corrosion of the iron container). The model calculations indicate that the fuel corrosion rate is almost independent of the selected diffusion length.

One of the purposes for developing the model is to understand the influence of H_2 on the fuel corrosion process. For this purpose, the model was used to calculate the critical H_2 concentration, which is defined as the H_2 concentration at which the oxidation rate of the fuel by H_2O_2 is equal to the rate of reduction of the fuel by H_2 (i.e., the H_2 concentration at which the net fuel dissolution rate is approximately zero).

Figure 5.1 shows a plot of the critical H_2 concentration as a function of the time after disposal for CANDU fuel with a burnup of 220 MWh/kgU. The critical H_2 concentration reaches a maximum of about 3×10^{-5} mol/L approximately 100 years after disposal (the time of the maximum alpha radiation dose from the fuel), and decreases substantially after about 10^4 years. The maximum critical H_2 concentration corresponds to a H_2 partial pressure of about 0.037 bars, a relatively low level. These results, which are consistent with experimental results, suggest that the hydrogen generated by corrosion of the inner steel vessel of the used fuel container could greatly limit the fuel corrosion rate (Shoesmith, 2008).

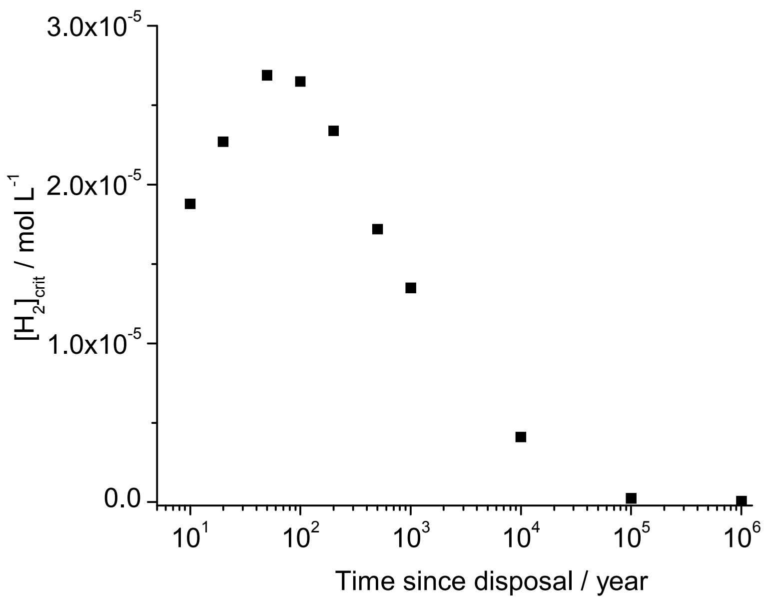

Figure 5.1: Critical H_2 Concentration as a Function of Time after Disposal for CANDU Fuel with a Burnup of 220 MWh/kgU

5.2.1.2 Influence of Fuel Composition on Fuel Reactivity

Work in previous years demonstrated the ability of dissolved H_2 to suppress fuel oxidation/dissolution by reaction on galvanically-coupled noble metal particles (Broczkowski et al., 2010; Broczkowski et al., 2011; Shoesmith, 2008), but H_2 seemed to have little influence on UO_2 surfaces not containing noble metal particles. The composition of the fuel, therefore, can have an important influence on fuel reactivity.

In 2011, the influence of rare earth doping on fuel reactivity was further investigated using 6 wt% gadolinium (Gd) doped UO_2. As demonstrated for air oxidation, rare earth doping could stabilize the UO_2 matrix against oxidation/dissolution. Rare earth doping could have the potential, therefore, to influence the reactivity of H_2O_2 on the UO_2 matrix, perhaps by inhibiting the anodic reaction. This hypothesis was investigated using electrochemical methods to compare the reactivity of Gd-doped UO_2 and SIMFUEL. The first step involved characterization of the Gd-doped UO_2 using Raman spectroscopy. The results indicate that the Gd-doped UO_2 possesses a highly distorted lattice compared to SIMFUEL samples.

Preliminary findings from the electrochemical experiments indicate that, although oxidation from U(IV) to U(V) seems the same for both Gd-doped UO_2 and SIMFUEL, the oxidation from U(V) to U(VI), and dissolution of U(VI), may be suppressed for the Gd-doped UO_2 relative to the SIMFUEL. In order to validate these results, additional work is being performed in 2012.

5.2.1.3 Hydrogen Peroxide Studies

Hydrogen peroxide, H_2O_2, which is formed by the alpha radiolysis of water, is the dominant oxidant in a failed used fuel container. Consequently, its behaviour is important for understanding the corrosion/dissolution of the fuel.

In 2011, investigation of the effect of H_2O_2 on the corrosion of UO_2 as a function of pH was continued, with an emphasis on defining the conditions when the decomposition of H_2O_2 is most favourable (i.e., if H_2O_2 decomposes it is not available for dissolving UO_2). At high pH (pH > 11.6, the acid dissociation constant of H_2O_2), it was found that H_2O_2 decomposition on SIMFUEL becomes important. This occurs because H_2O_2 oxidation is catalyzed on the noble metal particles, causing a rebalancing of the relative importance H_2O_2 decomposition and UO_2 dissolution. Given that the expected pH is much lower in a repository for used fuel, it is not immediately clear what these results mean for waste disposal conditions. Studies to determine the importance of decomposition under more relevant conditions (i.e., under assumed repository pH conditions) are underway.

5.2.1.4 Other Studies

A series of controlled, low current experiments were carried out to study the influence of corrosion product depositions on fuel corrosion. The expectation was that a corrosion product film would form on the surface of the UO_2 electrode, allowing a study of the influence of deposits on fuel dissolution. These experiments were unsuccessful, however, because of electrode issues (Beauregard, 2011). Other approaches are needed to study the influence of corrosion product deposits on fuel corrosion. With this goal in mind, the properties of uraninites and coffinite were reviewed by Beauregard (2011) with the aim to understand the potential for coffinite formation under repository conditions.

5.2.1.5 Instant Release Fractions

Radionuclides are released from used fuel by two processes – instant release and congruent dissolution release. Instant release is the rapid release of radionuclides upon contact with water, while congruent release is slower and occurs as the matrix material (either the UO_2 fuel or the Zircaloy cladding) dissolves. Data for instant release fractions for key elements (e.g., I, C, Sr, and Cs) are based on the experimental work of Stroes-Gascoyne (1996). The measurements are costly and therefore difficult to reproduce.

In late 2010, a work program was initiated to determine if it is possible to compute conservative, yet realistic, estimates of instant release fractions. To verify the approach, the 2009 release version of ORIGEN-S code was used to determine the post irradiation inventory, and the FEMAXI code v6.1 was used to calculate the instant release fractions, for comparison with representative measurements from Stroes-Gascoyne (1996). The chemical form of the radionuclides at the gap and grain boundaries was also determined using a Gibb's free energy minimization algorithm (Piro et al., 2010). After the verification step, the calculations were extended to different combinations of burnup and linear power ratings. The results, discussed in Iglesias et al. (2011), show that the FEMAXI v6.1 computed instant release fractions agree fairly well with the experimental results. The chemical speciation calculations confirmed the complete dissolution of Cs, I and Sr in 0.1 mol/L HCl, while compounds of Te, Tc and Pb are anticipated to be poorly soluble or insoluble.

For low fuel element linear powers, the computed instant release fractions show insignificant variation with burnup and radial location in the bundle. This occurs because the thermally activated release processes are not dominant contributors when compared to the release mechanisms that are independent of temperature. At higher powers, the instant release fractions show a marked dependency on the burnup, the radial location of the grain boundary inventories in the bundle, and the gap inventories.

5.2.2 Repository Modelling

The repository or near-field region includes the container, the surrounding buffer and backfill, other engineered barriers, and the adjacent host rock. Almost all radioactivity associated with the used fuel is expected to be isolated and contained within this area over the lifetime of the repository. On-going work with respect to repository safety in the near-field region is aimed at improving our understanding of the transport-limiting processes around a failed container. Work on container corrosion models carried out under the Repository Engineering program is described in Section 3.5.2.

5.2.2.1 Failed Container Model

The used fuel container is a barrier to the release of radionuclides. Initially it provides a barrier by preventing access of water to the used fuel. Eventually the containers will corrode or fail, and water will be able to enter and contact the contents. Residual radioactivity within the used fuel may thereafter be released into the contact water due to a combination of instant release (Section 5.2.1.5) and slow dissolution (Section 5.2.1).

For a copper container, the assumed non-corrosion failure mode that is evaluated for safety assessment purposes is via a weld defect that goes unnoticed during the fabrication and inspection processes. Typically a 1/5000 defect frequency is assumed, with the failure being a small "pinhole"-like defect whose area does not increase with time.

As part of the exploration of options for saline sedimentary rock conditions (see Fifth Case Study, Section 5.3.1.3), containers made exclusively of steel are being evaluated in the context of repository safety. These would be essentially identical to the copper containers, except the outer copper corrosion barrier would not be present. Because steel corrodes in the presence of water (or high humidity), it is possible that all containers will fail at some point during the safety assessment time frame and the failure mode for safety assessment evaluations is thus different from the "pinhole" defect for a copper container.

To assess the radionuclide releases associated with a completely failed container, the COMSOL code v4.2 has been used to model a corroded container in a placement room. Because the container is no longer an effective barrier, the flux of highly soluble elements is limited only by the fuel dissolution rate. The flux of solubility limited elements is also shown to increase substantially over that associated with the "pinhole" defect model. The results of this study will be used in future case studies involving steel containers to represent the container failure model. Documentation describing the details of this model is planned for 2012.

5.2.2.2 Radionuclide Solubility

The maximum concentration of radionuclides is limited by their solubility in water. Many potentially important radionuclides, such as plutonium, have very low solubilities under the conditions expected at the repository horizon, and will therefore never mobilize in large amounts.

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

Throughout 2009 and 2010, the solubilities of several key radionuclides used in the safety assessment models were updated. Currently, the thermodynamic method to calculate solubilities at very high salinities is ambiguous, so both the Pitzer (Specific-ion Interaction) and SIT (Specific Ion Theory) approaches are used. Both approaches require a thermodynamic database. The Pitzer dataset from the Yucca Mountain Project Dataset, converted to PHREEQC format, was used to determine radionuclide solubilities. The SIT approach used the ThermoChimie v6 dataset, developed by ANDRA, also in PHREEQC format.

The solubilities of Am, As, Bi, C, Cu, Mo, Nb, Np, Pa, Pb, Pd, Pu, Ra, Se, Sn, Tc, Th, U, and Zr were calculated in reference crystalline (CR-10) and sedimentary (SR-270) water compositions. The interaction of the buffer materials and the container on the groundwater chemistry was included in the solubility calculations. Both the Pitzer and SIT approaches produced similar solubility results for elements found in both datasets (Duro et al., 2010). No additional solubility work was completed in 2011; however, additional calculations for other highly saline brine compositions may be carried out in support of postclosure safety case studies for sedimentary rock geospheres in the future.

5.2.2.3 Thermodynamic Database Review

NWMO continues to support the joint international Nuclear Energy Agency effort on developing thermodynamic databases for elements of importance in the safety assessment for used nuclear fuel (Mompeán and Wanner, 2003). The fourth phase of the Thermochemical Database (TDB) Project began in February 2008 and will continue until 2012. The initial focus is to finalize reviews of chemical thermodynamic data for inorganic compounds and complexes of thorium, iron and tin. In late 2008, the thorium thermodynamic data report was published (Rand et al., 2008). The reviews of tin and the key species of iron (Fe(II) and Fe(III)) are in their final form and they are expected to be published once reviews of other species and compounds of iron are complete.

Due to the high salinity of brines observed in sedimentary and crystalline rocks in Canada, a thermodynamic database including ion interaction parameters is needed for radionuclide solubility calculations. In 2008, the Yucca Mountain Project (YMP) Pitzer database "data0.ypf.R2", which includes Pitzer ion interaction coefficients developed by Sandia National Laboratories (USDOE, 2007), was converted from EQ3/6 format to PHREEQC format (Benbow et al., 2008). To test the suitability of the database for Canadian conditions, results were compared with other Pitzer thermodynamic databases using the standard PHREEQC package and the SIT thermodynamic database, ThermoChimie (Duro et al., 2010).

In 2011, a more extensive evaluation of this database was performed, focusing primarily on the representation of the Pitzer model to the experimental data. Thermodynamic properties of silicates, especially clay minerals, were also examined. Recommendations were made to develop a new Pitzer database that is internally consistent and suitable for Canadian geology. To develop such a database, the mineralogies of sedimentary rocks in southwestern Ontario and western Canada, and crystalline rocks in the Canadian Shield, were summarized. Solid phases relevant to Portland cement-based systems were also reviewed.

5.2.2.4 Gas Transport through Buffer

Corrosion of steel in the repository will result in the slow generation of gases. The low-permeable clay seal around the container will retain these gases until a threshold pressure is reached, after which they will escape. This is of interest for understanding behaviour in the near-field around a failed container. To explore this area, a full-scale in-situ test, LASGIT, was initiated several years ago in the SKB Äspö Hard Rock Laboratory in Sweden, to which NWMO is contributing in the gas transport modelling component.

Version 2.0 of the TOUGH2, two-phase transport code was selected as the reference code and was then modified for LASGIT to simulate pressure-induced changes in properties such as micro- and macro- fracturing. In 2006 and 2007, the modified code was applied to laboratory experimental data (MX-80-10 conducted by Harrington and Horseman, 2003) and predictive simulations of the LASGIT experiment. Results of the preliminary gas tests performed in 2008 at LASGIT were analysed in 2009. The results were difficult to interpret, but seemed to indicate that gas breakthrough had occurred; however, it was concluded that the experimental system may not have been fully saturated and may have been producing unreliable data.

In 2011, 3D simulations using the modified TOUGH2, and homogeneous/heterogeneous permeability fields in bentonite, were performed to model the 2009 gas injection test results, which showed complex gas propagation behaviour through the bentonite. Models using heterogeneous permeability fields were more successful than the homogeneous permeability field model. A heterogeneous permeability field model successfully simulated the pressure drop at the injection port and a rapid pressure increase at the rock-wall. The pressure increase at the rock-wall took a minimum of 5 days, which is much longer than the experimental value of 1.5 days (see Figure 5.2).

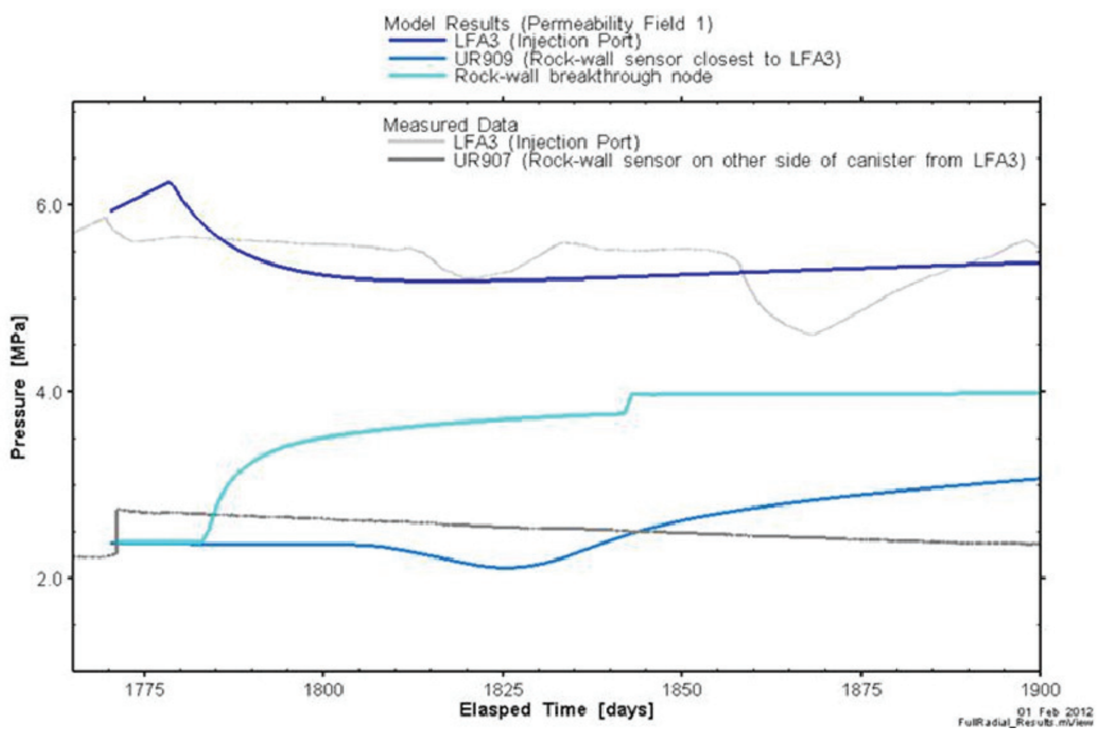

Figure 5.2: Modelled Injection and Rock-Wall Pressures Using Heterogeneous Permeability Fields for LASGIT 2009 Gas Injection Test

All models showed gas reaching the rock-wall immediately adjacent to the injection port, rather than, as observed, on the opposite side of the container. Several model modifications are recommended, particularly in the methods by which pressure-induced permeability and capillary pressure are calculated, in order to improve the ability of the model to simulate a distinct gas pathway at a location that is not immediately adjacent to the injection port.

5.2.2.5 Shaft Seal Properties

In the existing safety assessment and engineering design studies, the key transport and performance properties (i.e., swelling pressure and hydraulic conductivity) for the 70/30 bentonite-sand shaft seal material have been interpolated from existing data for other bentonite based materials. Neither testing for specific shaft seal materials, nor testing for saline groundwater conditions, has been carried out at this time. In 2011, NWMO initiated a series of basic physical and mechanical tests on the bentonite-sand mixture to establish the effect of groundwater salinity on its behaviour. The tests included:

- Compaction characterization;
- Swelling pressure and hydraulic conductivity tests;
- Determination of bulk modulus and Young's modulus of material using triaxial isotropic consolidation tests and/or 1D-consolidation tests;
- Gas permeability tests; and
- Determination of the soil-water characteristic curve (SWCC).

Two independent laboratories were retained to carry out the analyses. Other than compaction characterization, which is equivalent to the Modified Proctor Method (ASTM D1557-78), the other tests listed are on-going and will continue into 2012. For the compaction test, the Optimum Moisture Content for the bentonite-sand mixtures is minor and ranges between 15 and 16.5%. The range of measured maximum dry densities was also small, and found to vary between 1.77 and 1.88 Mg/m^3, with the highest maximum dry densities measured in the bentonite-sand mixtures blended with relatively high salinity reference groundwaters.

5.2.3 Geosphere (or Far-field) Modelling

The development of improved geosphere models is largely carried out under the Geoscience work program. Recent safety assessment case studies have used both detailed geosphere models and system-level safety assessment models. In particular, the Third Case Study and Third Case Study/Horizontal Borehole Concept studies (Gierszewski et al., 2004; Garisto et al., 2005) have used a regional study model similar to that used in on-going Geoscience numerical studies and the FRAC3DVS code (see Section 4.3.1.2) in order to provide detailed 3D groundwater flow and transport analyses. This ensures that the same geosphere conceptual model is being used by both the geoscience and safety assessment groups. The Fourth Case Study (Section 5.3.1.2), initiated in late 2009, considers crystalline rock with a different container design and a different repository depth.

To date, the NWMO and its subcontractors have used the numeric code FRAC3DVS-OPG to perform site-scale detailed 3D flow and transport simulations. Simulations with COMSOL v4.1, a finite element code with similar capabilities to FRAC3DVS-OPG, were performed to provide further validation cases for FRAC3DVS-OPG and to evaluate the suitability of COMSOL for large-scale groundwater and radionuclide transport modelling.

The first component of the assessment consisted of a comparison of simple 1D, 2D and 3D test cases. Results for FRAC3DVS-OPG and COMSOL were found to be virtually identical, with the exception of some discrepancies in calculated drawdown at flux withdrawal nodes. The discrepancies were demonstrated to be related to discretization, and do not reflect errors in the numerical implementation. This suite of simulations provided a useful collection of validation test cases for FRAC3DVS-OPG.

Subsequently, results for flow and transport on a large-scale model (>4M nodes), typical of those used in NWMO safety assessments, were compared. Flow simulation comparisons of the two codes showed very good agreement on calculated hydraulic heads, with some minor variations found in portions of the grid where element thickness varied. The variations are minor and do not affect model usability. These large scale model comparisons are useful in building confidence in the FRAC3DVS-OPG flow model implementation on the scale and heterogeneity typically employed for safety assessment.

Transport solutions using COMSOL on the large-scale model proved difficult. Results were obtainable for only a limited part of the total simulation period. Based on these results, it was concluded that the COMSOL model, as currently constituted and with currently available processors, is not suitable for large scale transport calculations of interest to NWMO safety assessment.

5.2.4 Biosphere Modelling

5.2.4.1 Environmental Radioactivity

Postclosure safety assessments use environmental concentrations and fluxes of radionuclides as long-term safety indicators. Knowledge of background radioactivity is useful as a criterion or reference point for these indicators, especially if the data are regionally appropriate. Environmental radioactivity measurements were done in 2010 to complement a literature review completed in 2009 on a summary of background concentrations of radionuclides in surface waters and soils across Canada. The results of the environmental radioactivity measurements were published in Sheppard and Sanipelli (2011).

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

Gaps in information were identified in the 2009 review. In particular, there were few data for ^{129}I and ^{36}Cl. Additionally, the degree of disequilibria in U and Th decay series was not well characterized. These gaps were addressed by taking background radioactivity measurements of twenty-one surface waters from New Brunswick to Saskatchewan. Analysis of the samples for ^{129}I and ^{36}Cl was performed by Accelerator Mass Spectroscopy and for U and Th progeny by radiochemical methods. Trace elements and tritium were also measured. The observed concentrations of ^{129}I, ^{36}Cl and ^{3}H were consistent with expectations, and the present study increased the number of data points available for Canadian waters by several fold. Concentrations of ^{232}Th, ^{235}U and ^{238}U were detectable at all locations, with substantial data ranges. The U and Th decay series radionuclides were seldom detectable in water. Data were obtained for ^{129}I and several U and Th decay series radionuclides in a few soil and rock samples.

The overall results of the project, which combines the results from the literature review and the measurements, were published in Sheppard et al. (2011).

5.2.4.2 Non-Human Biota

From 2008-2010, the NWMO developed and expanded a screening methodology for assessing the potential postclosure impact of a deep geological repository for used fuel on non-human biota. The screening was carried out by comparing estimated radionuclide concentrations to derived “No Effect Concentrations” (NECs), which are screening or threshold criteria.

Work in 2009-2010 expanded on the original work published in Garisto et al. (2008) to include more biota, more radionuclides and updated transfer factors. Because this is an area with significant international development in the past few years, an assessment of the NWMO’s current position regarding criteria for radiological impacts on non-human biota was performed in 2011, informed in part through participation in the international BIOPROTA project. The analysis discussed the different types of screening criteria (NEC versus dose rate criteria), reference values for dose coefficients, estimated no-effect values and relative biological effectiveness, as well as reference datasets for transfer factors and concentration ratios.

Although no reference position has yet been chosen, an updated non-human biota dose assessment method is expected to be developed in 2012, which will take into account the recommendations received in 2011. This information will be used to guide future NWMO activities and research approaches in this subject area.

5.2.4.3 Participation in BIOPROTA

BIOPROTA is an international collaborative forum, which seeks to address key uncertainties in the assessment of radiation doses in the long-term arising from the release of radionuclides as a result of radioactive waste management practices. Participation is aimed at national authorities and agencies, with responsibility for achieving safe and acceptable radioactive waste management.

In 2011, the NWMO hosted the annual meeting (in Hamilton, Ontario) and financially supported three BIOPROTA projects: the ^{238}U Project, the Non-Human Biota Project and the Human Intrusion Project.

^{238}U Project

The purpose of the ^{238}U Project was to improve confidence in long-term dose assessments for ^{238}U series radionuclides relevant to a used fuel repository. The ultimate goal was to improve understanding of: 1) disequilibrium in the decay chain within geosphere-biosphere interface zones, 2) radon emanation rates, and 3) the effect of environmental change.

The project focused on comparisons of calculated concentrations of ^{238}U, ^{234}U, ^{230}Th and ^{226}Ra in soil and plants for geosphere to biosphere release scenarios (i.e., contaminated groundwater) for a hypothetical and an actual site. The actual site is a decommissioned mine site in Spain, for which model parameters, such as soil texture and distribution coefficients and soil-plant transfer factor data, are determined using empirical measurements. Seven models, including NWMO’s SYVAC-CC4 soil model, were used in the qualitative model inter-comparison (which had the added benefit of serving as a confidence building exercise for the SYVAC-CC4 soil model).

The project was financially supported by the NWMO together with ANDRA, CIEMAT (Spain; Centre for Energy, Environment and Technology Research), ENRESA (Spain; National Radioactive Waste Management Agency), NDA RWMD (Nuclear Decommissioning Authority Radioactive Waste Management Directorate), NUMO (Nuclear Waste Management Organization of Japan) and SKB. Results from these analyses will be published in 2012, together with a discussion of interpretation of site data and implications for improving confidence in long-term dose assessments for ^{238}U series radionuclides. The work was presented by

BIOPROTA at the International Conference on Radioecology and Environmental Radioactivity in Hamilton in June 2011.

Non-Human Biota Project

In 2009 and 2010, a work program was undertaken to identify key uncertainties and data gaps inherent in non-human biota dose assessments, specifically relating to deep geological disposal facilities for radioactive waste. The project was financially supported by the NWMO in collaboration with POSIVA, NRPA (Norwegian Radiation Protection Authority), SKB, ANDRA and SSM (Swedish Radiation Safety Authority). The final report is expected to be published in 2012.

As a result of this study, a number of issues relevant to safety assessment were raised. In particular, while the study has increased understanding of the derivation of screening levels used in preliminary assessments for impacts to non-human biota, it has also raised awareness regarding a lack of guidance on the application of screening values, the interpretation of assessment results, and the appropriate response when screening levels are breached.

The current project was aimed at providing information on the interpretation of results of dose assessments for non-human biota relevant to scenarios where either generic or site-specific assessments are required, and where screening levels are exceeded. It is designed to support the demonstration of compliance with protection objectives for non-human biota within postclosure safety cases for radioactive waste repositories.

BIOPROTA proposed a two-tier, three zone framework, relevant to the long-term assessment of potential impacts. The purpose of the assessment framework and associated material is to promote a proportionate and risk-based approach to the level of effort required in undertaking and interpreting an assessment. The zoned structure is not intended to present hard and fast rules for the nature and detail of an assessment to be undertaken, but instead to provide direction on the approach and the amount of site-specific information that may be required.

Human Intrusion Project

For near-surface disposal, approaches for the assessment of human intrusion have been developed through international cooperation within the International Atomic Energy Agency's (IAEA) through the ISAM (Improving Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities) programme. Various assessments have considered intrusion into deep geological disposal facilities, but comparable international cooperation to develop an approach for deep disposal has not yet taken place.

The particular objectives of the project are to:

- Examine the technical aspects of why and how such intrusion might occur;
- Consider how, and to what degree, exposure to the people involved would follow;
- Identify the processes which constrain the uncertainties; and
- Develop and document a reference approach for evaluation of the human intrusion doses.

Based on the results of the first three items, the most likely cause of intrusion is taken to be various forms of geological or other investigation by borehole drilling. However, the reasons for investigation have little effect on how radiation exposure would most likely arise as a consequence. Accordingly, simple models have been constructed for assessing dose via external irradiation, inhalation of dust and ingestion, which are considered applicable to a wide range of drilling intrusion scenarios.

The results of the assessment have been applied to illustrative examples of high level and low/intermediate level waste packages and waste disposal systems to demonstrate how the results can be applied to real environs. In addition, consideration has been given to factors which influence the scale and likelihood of such intrusions and exposures, as well as the implications for meeting international recommendations on protection objectives in this context. The project was financially supported by the NWMO together with POSIVA, SSM and NUMO. The final report is expected to be published in 2012.

5.2.5 Integrated System Model

The postclosure safety assessment of a used fuel repository uses several complementary computer models (Table 5.2). These are either commercially maintained codes, or codes maintained by NWMO under a software quality assurance system.

Table 5.2: Main Safety Assessment Codes for Postclosure Analyses

Software	Description / Use
SYVAC3-CC4	Reference integrated system model
FRAC3DVS	Reference 3D groundwater flow and transport code
TOUGH2	3D two-phase gas and water flow code
AMBER	Generic compartment modelling software
COMSOL	3D multi-physics finite element modelling software
PHREEQC	Geochemical calculations code
MICROSHIELD	Radioactive shielding and dose code

The main software activity in 2011 was the release of the new integrated system model SYVAC3-CC4 v8 (NWMO, 2011) and the corresponding reference dataset designed for use in the Fourth Case Study (Section 5.3.1.2). Additional software development activities include the release of new versions of the pre- and post-processing programs used to format input data and display output data for the system model.

In late 2011, the change control process was initiated to update CC4.08 for use in the Fourth Case Study and in the upcoming Fifth Case Study. Significant changes included 1) removing hardwired geosphere coding from SYVAC3-CC4, 2) incorporating an update to the well selection logic, and 3) implementing various updates to the biosphere model.

5.3 CASE STUDIES

The objective of safety case studies is to provide illustrative examples of repository safety under various conditions and to test or demonstrate NWMO's safety assessment approach.

Three major safety assessment postclosure case studies have been considered within the Canadian program, these being 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., 2004). These case studies provided an opportunity to assess and illustrate the safety implications of the repository concept in the Canadian Shield. Additional progress has been made in 2011 on the Glaciation Scenario, the Fourth Case Study and the Fifth Case Study, as described below.

In addition, a preclosure study examined postulated releases of radioactivity during normal and accident conditions to determine the minimum required distance to the site boundary. A generic transportation study has also been undertaken to determine anticipated doses to workers and members of the public for normal conditions of transport. These studies are also described in the following sections.

5.3.1 Postclosure Case Studies

5.3.1.1 Glaciation Scenario

The 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 of 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 climate trends will continue and that the onset of the next glaciation will be delayed, but in the long run it is prudent to assume that the glacial cycles will resume following the long-term variation in solar insolation due to earth's orbital variations.

During past glacial cycles, much of Canada has been covered by kilometres-thick ice sheets. Because these glacial cycles represent such a large potential perturbation to a site, the Canadian used fuel program has been examining the implications of glaciation for many years (see, for example, Section 4.3.1 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 2009, the effects of an evolving climate with multiple glaciations were quantitatively evaluated from a safety assessment perspective within the context of the hypothetical Third Case Study site on the Canadian Shield. The purpose of this Glaciation Scenario case study was to quantitatively assess the long-term dose implications of glacial cycles for a repository and to understand the key factors involved. The results of this study, which were summarized in previous annual reports, were published in 2010 in two peer-reviewed reports: Garisto et al. (2010) and Walsh and Avis (2010). The study concluded that the potential releases would remain well below regulatory limits, even when the effects of glaciation are considered. The results of the Glaciation Scenario study were presented to SKB and at the BIOPROTA annual meeting in Stockholm in 2010.

As the durations of future glaciation states are uncertain, the Glaciation Study included a probabilistic case where the durations of all climate states (approximately 100 modelled during the 1 Ma time frame) were varied in each of 1200 simulations, while the other parameters remained at their reference case values. In 2011, this work was expanded to include an additional probabilistic case where climate states within the first glacial cycle were varied randomly, then filling the balance of the 1 Ma with glacial cycles identical to the first. Detailed analysis suggested that the occurrence of long ice sheet states during glacial cycles could lead to higher peak dose rates. The results were interpreted with caution based on the model simplifications necessary to allow for probabilistic climate states.

5.3.1.2 Fourth Case Study

The Fourth Case Study builds on the series of postclosure safety assessments for a deep geological repository in crystalline rock. Key differences relative to the Third Case Study are the shallower depth (500 m) of the repository, the use of in-floor placement, larger container geometry, a greater number of fuel bundles, and an updated reference geosphere.

The study is intended to determine hypothetical radiological and non-radiological impacts to humans and non-human biota for a range of Normal Evolution and Disruptive Event scenarios. Modelling and assessment for these scenarios are based on information that is expected to be available during the site evaluation stage of a feasibility study, prior to exploratory drilling.

The used fuel container consists of an outer copper vessel, an inner steel vessel, and three steel baskets (as shown in Figure 3.4). The copper vessel provides a corrosion-resistant barrier in the repository environment. The inner vessel is designed to withstand any mechanical stresses, including stresses due to glaciation. Each container has the capacity for 360 used fuel bundles, distributed in six layers of 60 bundles each, and held in three baskets that are stacked on top of each other inside the inner vessel (two layers per basket).

Once placed in the repository, used fuel containers are surrounded by compacted bentonite clay. All excavated spaces are filled with mixtures of clay, sand, and rock to minimise the flow of water. In addition, placement rooms are sealed with bulkheads of special high-performance concrete. Shafts are similarly filled and sealed, isolating the repository from the biosphere.

The geosphere is composed of granitic rock, characterised by a statistically generated discrete fracture network. Sensitivity studies will examine the effect of geosphere permeabilities.
The study considers both Normal Evolution and Disruptive Event scenarios, together with a range of associated sensitivity studies performed to illustrate the insensitivity of results to assumed degradations in the engineered and natural barriers. Both deterministic and probabilistic simulations are underway, and preliminary results indicate that all radiological and non-radiological acceptance criteria are anticipated to be met within substantial margins.

Preliminary results were obtained in 2011. The final analysis and report are to be completed in 2012.

5.3.1.3 Fifth Case Study

Scoping and planning activities for the Fifth Case Study, a postclosure safety assessment for a deep geological repository for used fuel in sedimentary rock, were also initiated in 2011. For this rock type, both copper shell and steel-only containers are under consideration both in Canada and internationally.

The main focus of 2011 work activities for the Fifth Case Study was:

- Conducting scoping studies on gas generation and transport with FRAC3DVS-OPG and TOUGH2 GGM; and
- Revising the SYVAC3-CC4 system model to include gas transport.

The generation, accumulation, and release of gas from a repository system is of interest to many international radioactive waste isolation programs, such as NAGRA (Switzerland), ANDRA (France), and ONDRAF/NIRAS (Belgium). The European Community's FORGE (Fate Of Repository GasEs) project is a pan-European project, with links to international radioactive waste management organizations, regulators and academia. The project is specifically designed to address key research issues associated with the generation and movement of repository gases. A key contribution of the NWMO work to FORGE is advancing the level of understanding in this field by coupling the container corrosion with the availability of water.

In the scoping studies, parameters describing carbon steel corrosion under anticipated repository conditions were defined using a comprehensive selection of published experimental results. Bentonite resaturation behaviour was defined using experimental results from the LASGIT program (LArge Scale Gas Injection Test) at SKB (Sweden).

This modelling program will continue in 2012 and will expand to include migration of gas through the repository, as well as additional sensitivity analyses.

5.3.2 Preclosure Studies

5.3.2.1 Site Boundary for Surface Operations at a Deep Geological Repository

Postulated radiological emissions due to surface operations at a hypothetical deep geological repository have been used to estimate the minimum distance to the site boundary necessary to ensure any consequent dose to members of the public during the preclosure (or operational) period would not exceed the associated CNSC regulatory dose limit.

Public dose was calculated at distances ranging from 100 m to 1500 m from the aboveground Used Fuel Packaging Plant ventilation exhaust, where 100 m coincides roughly with the position of the facility's perimeter fence in the current design and represents the minimum distance for which the applied air dispersion model is valid. Environmental pathway analyses were performed as outlined in guidelines N288.1 and N288.2 of the Canadian Standards Association.

In 2011, the scope of this assessment was expanded to include sensitivity to the design of the ventilation exhaust, specifically the resulting atmospheric dilution.

Normal Operations of the repository surface handling facilities may result in emissions of radioactivity (for example, emissions resulting from the established routines of fuel receipt, transportation, and subsequent re-packaging into long-lived containers). Conservative estimates of chronic public dose consequences due to Normal Operations were several orders of magnitude below the regulatory dose limit of 1 mSv/a.

Anticipated Operational Occurrences are considered outside the range of normal operations, but are assumed to occur with frequencies of at least 10^{-2} per year. Several Anticipated Operational Occurrences were considered in this assessment, including: 1) an Irradiated Fuel Transportation Cask carrying water from an Irradiated Fuel Bay; 2) significantly longer transportation or staging times; 3) an increased processing load; and 4) an increase in pre-existing fuel sheath failures. In 2011, failure of the ventilation exhaust filtration system was added as an Anticipated Operational Occurrence. Conservative estimates of the consequent public dose are several orders of magnitude below 1 mSv.

Design Basis Accidents are outside the range of Anticipated Operational Occurrences and are assumed to occur with frequencies of between 10^{-2} and 10^{-5} per year. Postulated Design Basis Accidents considered in this assessment are: 1) scissor lift failure causing an Irradiated Fuel Transportation Cask to fall; and 2) overhead carriage failure causing one used fuel module to fall onto another module. All accident scenarios are considered both with and without concurrent failure of the emergency High Efficiency Particulate Air (HEPA) filtration system. Predicted acute public dose consequences from the Design Basis Accidents are well below 1 mSv. A report documenting this work is planned for issue in 2012.

5.3.2.2 Transportation Safety

An update to the generic risk assessment for the transport of used nuclear fuel from interim used fuel storage sites to a hypothetical repository site was initiated in late 2010. The intent of this work is to update the previous assessment (OHN, 1994) through the incorporation of current system design assumptions. The assessment examines the risks associated with used fuel transport by the three surface modes (road, rail and water) of transport during normal and accident conditions, as defined within the transportation regulations. The results will support APM community engagement by addressing public concerns about the safety of the transportation system and its associated risks. The analysis and associated documentation will be completed in 2012.

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APPENDIX A: TECHNICAL REPORTS, RESEARCH PAPERS, CONTRACTORS AND AWARDED SCHOLARSHIPS

A.1 NWMO TECHNICAL REPORTS

Bea, S.A., K.U. Mayer and K.T.B. MacQuarrie. 2011. Modelling reactive transport in sedimentary rock environments – Phase II, MIN3P code enhancements and illustrative simulations for a glaciation scenario. Nuclear Waste Management Organization Report **NWMO TR-2011-13**. Toronto, Canada.

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A.2 PUBLICATIONS AND PRESENTATIONS

Refereed Journals

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Broczkowski, M.E., D. Zagidulin and D.W. Shoesmith. 2010. The role of dissolved hydrogen on the corrosion/dissolution of spent nuclear fuel. In Nuclear Energy and the Environment, American Chemical Society Symposium Proceedings, Vol. 1046, Chapter 26, 349-380.

Eriksen, T.E., D.W. Shoesmith and M. Jonsson. 2012. Radiation induced dissolution of UO_2-based nuclear fuel – A critical review of predictive modelling approaches. J. Nucl. Mater., 420, 409-423.

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Conference Presentations & Proceedings Papers

Bea, S.A., K.U. Mayer and K.T.B. MacQuarrie. September 2011. Modelling of reactive transport in a sedimentary basin affected by a glaciation/deglaciation event. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Beauheim, R., R.M. Roberts, J.D. Avis and D. Heagle. September 2011. Hydrogeological Evidence of Low Rock Mass Permeabilities in Ordovician Strata: Bruce Nuclear Site. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Clark, I., T. Al, M. Jensen, L. Kennell, K. Raven. September 2011. Hydrogeochemical Characterization of Groundwaters and Porewaters Beneath the Bruce Nuclear Site: Evidence for Diffusion-Dominated Transport in the Ordovician. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Garisto, F., R. Walsh, L. Wojciechowski, J. Avis, T. Chshyolkova, P. Gierszewski, M. Gobien, C. Kitson, T. Melnyk and J. Miller. April 2011. Safety Assessment of a Glaciation Scenario. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Garisto, N.C., A.D. Janes, R.L. Kovacs and C. Medri. June 2011. Developing Screening-Level No-Effect Concentrations (NECs) For Non-Human Biota to Assess Potential Radiological Impact of a Deep Geological Repository. International Conference on Radioecology and Environmental Radioactivity. Hamilton, Canada.

Gobien, M., J.D. Avis, T. Chshyolkova, F. Garisto, P. Gierszewski, N.G. Hunt, C.I. Kitson, E.P. Kermer, C.L.D. Medri, T.W. Melnyk, L.C. Wojciechowski. April 2011. Probabilistic Transport Modelling in a Canadian Used Fuel Repository. International High-Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Hirschorn, S., A. Vorauer, M.Ben Belfadhel, M. Jensen. September 2011. Glaciation and Geosphere Evolution – Greenland Analogue Project. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Hunt, N. G., E. P. Kremer, F. Garisto, P. Gierszewski, M. Gobien, C. L. D. Medri, J. D. Avis, T. Chshyolkova, C. I. Kitson, W. Melnyk and L. C. Wojciechowski. September 2011. Postclosure Safety Assessment of a Deep Geological Repository for Canada's Used Nuclear Fuel. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Kremer, E.P., J. D. Avis, T. Chshyolkova, F. Garisto, P. Gierszewski, M. Gobien, N. G. Hunt, C. I. Kitson, C. L. D. Medri, T. W. Melnyk and L. C. Wojciechowski. April 2011. Postclosure Safety Assessment of a Deep Geological Repository for Canada’s Used

Nuclear Fuel. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Kremer, E.P. and N.C. Garisto. September 2011. Dose Considerations for a Site Boundary for Surface Operations at a Deep Geological Repository. Waste Management, Decommissioning and Environmental Restoration, Canadian Nuclear Society. Toronto, Canada.

Lang, L. and A. Khan. April 2011. Pre-project Review of a Proposed Canadian Deep Geological Repository for Used Fuel. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Limer, L., A. Albrecht, M.-O. Gallerand, F. Garisto, C. Medri, S. Norris, D. Perez-Sanchez, M. Thorne and G. Smith. June 2011. Improving Confidence in Long-Term Dose Assessment for U-238 Series Radionuclides. International Conference on Radioecology and Environmental Radioactivity Proceedings. Hamilton, Ontario.

Normani, S.D. and J.F.Sykes. September 2011. Sensitivity Analysis of a Coupled Hydro-mechanical Paleo-climate Model of Density-dependant groundwater Flow in Discretely Fractured Crystalline Rock. CNS meeting proceedings.

Parmenter, A., M. Jensen, R. Crowe and K. Raven. September 2011. Explorability and Predictability of the Paleozoic Sedimentary Sequence beneath the Bruce Nuclear Site. CNS meeting proceedings.

Russell, S., A. Murchison and D. Wilson. April 2011. Reference Used Fuel Repository Designs in Crystalline and Sedimentary Rock. International High Level Radioactive Waste Management (IHLRWM) Conference Proceedings. Albuquerque, New Mexico.

Russell, S. September 2011. Overview of Adaptive Phased Management Repository Design Development. CNS meeting proceedings.

Shaver, K. and J. Facella. April 2011. Site Selection for Canada's National Repository for Used Nuclear Fuel. International High Level Radioactive Waste Management (IHLRWM) Conference Proceedings. Albuquerque, New Mexico.

Sheppard, S.C., M. Herod and C. Medri. June 2011. New background data for ^{129}I, ^{36}Cl and U/Th-series radionuclides in Canadian rivers. International Conference on Radioecology and Environmental Radioactivity Proceedings. Hamilton, Ontario.

Sheppard, S.C and M. Herod. 2011. Variation in background concentrations and specific activities of 36-Cl, 129-I and U-Th-series radionuclides in surface waters. Journal of Environmental Radioactivity 106 (2012) 27-34.

Sykes J., S.D. Normani, Y. Yin and M. Jensen. September 2011. Hydro-geologic Simulation of a Deep Seated Groundwater System: Bruce Nuclear Site. CNS meeting proceedings.

Vilks, P. September 2011. Radionuclide sorption and transport in brine solutions. CNS meeting proceedings.

Invited Presentations

Ben Belfadhel, M. 2011. The Long Term Management of Used Nuclear Fuel in Canada. Seminar. Lakehead University, November 18.

Birch, K. 2011. Overview of Adaptive Phased Management and the NWMO Engineering R&D Program. Guest Lecture. Queen's University, March 3.

Jensen, M. 2011. The Nuclear Waste Management Organization: Geosciences Overview. Seminar. University of Toronto Scarborough, November 14.

McKelvie, J. 2011. Geoscience Research and Development Related to the Long Term Management of Canadian Used Nuclear Fuel. Guest Lecture. University of Toronto Scarborough, February 11.

McKelvie, J. 2011. NWMO microbiology research supporting development of a DGR for used nuclear fuel. Mont Terri Joint Technical Discussion Meeting, February 24-25.

A.3 SCHOLARSHIPS

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

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

Ghazvinian, Ehsan. Fracture initiation and propagation in sedimentary rocks: Implications for excavation damage zone (EDZ). Queen's University. Supervisor Dr. Mark Diederichs.

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

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

Perras, Matthew. Investigation of the Development and Behaviour of Excavation Damage Zones Associated with Tunnel Construction for Nuclear Waste Repositories in Sedimentary Rocks: Applications for Optimization of Excavation Method and EDZ Cut-off Design. Queen's University. Supervisor Dr. Mark Diederichs.

Saso, Joe. Hydrogeochemical investigation of diagenesis and fluid-migration history in sedimentary basins. University of New Brunswick. Supervisor Dr. Tom Al.

MITACS Accelerate internship (co-funded by NWMO)

Beauregard, Y.A. (Master's). Corrosion behaviour of UO_2 and modelling radionuclide releases from defective containers. University of Western Ontario, Chemistry Department. Supervisors Dr. D. Shoesmith and Dr. S. Rohani. NWMO Supervisor: F. Garisto.

Thesis:

Beauregard, Y.A. 2011. Electrochemical and computational modelling studies on spent fuel dissolution and the effect of corrosion product deposits on UO_2 corrosion. M. Eng. Sci. Thesis, University of Western Ontario, Canada.

A.4 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

Alberta Innovates – Technology Futures
AMEC-NSS
Amphos21
AECL
Babcock & Wilcox
Candesco Corporation
Centre for Excellence in Mining Innovation
Chandler, N.
Columbia University (Dr. L. Seeber and Dr. K. Jacob)
COMSOL
David P. Jackson & Associates Limited
ECOMatters Inc.
Engineering Simulations Inc.
Gascoyne GeoProjects Inc.
Geofirma Engineering
GMS Abingdon Ltd./BioProta Group
Golder Associates Ltd.
G.R. Simmons & Associates Consulting Services Ltd.
Integrity Corrosion Consulting Ltd.
McGill University (Dr. P. Selvadurai)
Natural Resources Canada (formerly Geological Survey of Canada)
Queen's University (Dr. M. Diederichs)
Quintessa Ltd.
Royal Military College of Canada (Dr. G. Siemens, Dr. B. Lewis)
RSRead Consulting Inc.
Ryerson University (Dr. G. Wolfaardt)
SENES Consultants Ltd.
SKB International Consultants
SNC Lavalin Nuclear
TerraTek, A Schlumberger Company
Université Laval (Dr. R. Therrien)
University of Alberta (D. Martin)
University of Bern (Dr. M. Mazurek)
University of British Columbia (Dr. U. Mayer, Dr. S. Siddiqua)
University of Manitoba (Dr. J. Blatz)
University of New Brunswick (Dr. T. Al, Dr. K. MacQuarrie)
University of Ontario Institute of Technology (Dr. B. Ikeda)
University of Ottawa (Dr. I. Clark)
University of Toronto (Dr. R.C. Newman, Dr. P. Young, Dr. W. Peltier, Dr. B. Sherwood Lollar)
University of Waterloo (Dr. J. Sykes, Dr. S. Normani, Dr. Y. Yin, Dr. E. Reardon)
University of Western Ontario (Dr. D. Shoesmith, Dr. W. Nesbitt)
United States Geological Survey

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2011

ABSTRACT

Title: **RD&D PROGRAM 2011 – NWMO'S PROGRAM FOR RESEARCH, DEVELOPMENT AND DEMONSTRATION FOR LONG-TERM MANAGEMENT OF USED NUCLEAR FUEL**
Report No.: **NWMO TR-2011-01**
Author(s): J. Villagran, M. Ben Belfadhel, K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, A. Khan, E. Kremer, G. Kwong, T. Lam, P. Maak, J. McKelvie, C. Medri, A. Murchison, S. Russell, M. Sanchez-Rico Castejon, U. Stahmer, E. Sykes, A. Urrutia-Bustos, A. Vorauer, T. Wanne and T. Yang
Company: Nuclear Waste Management Organization
Date: April 2011

This report describes the state of knowledge, rationale and planned work program activities of the Nuclear Waste Management Organization's Adaptive Phased Management Technical Program over the period 2011 to 2015. It is the first of a series of reports that describe the planned work program and support the primary objective of completing preliminary designs, safety cases, cost estimates and generic research activities for a used fuel deep geological repository to support a licence application following the planned selection of a preferred site by 2018.

The two main work areas of the Adaptive Phased Management Technical Program are:

(1) Developing deep geological repository designs and associated safety cases necessary to ensure that the Nuclear Waste Management Organization has the appropriate level of engineering design and demonstrated repository safety to support a future application for a site licence; and

(2) Building confidence in the safety case and improving our understanding of processes in the repository that may affect both the near and long-term safety.

Important technical work is also planned in areas of geoscience relevant to site characterization and evaluation to support site screening, feasibility studies of candidate sites and the planned selection of a preferred site by 2018. Also, work will be conducted to maintain awareness of alternative technologies and new developments for managing used nuclear fuel over the long-term.

The report reviews the status of research, development and demonstration of used nuclear fuel properties, used fuel containers, sealing materials, geoscience processes, repository performance modelling, safety assessment and transportation. It describes specific research and engineering activities including the participation in joint international projects and demonstrations of repository technology.

ABSTRACT

Title: **TECHNICAL PROGRAM FOR LONG-TERM MANAGEMENT OF CANADA'S USED NUCLEAR FUEL – ANNUAL REPORT 2010**
Report No.: **NWMO TR-2011-02**
Author(s): J. McKelvie, K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, M. Jensen, A. Khan, E. Kremer, G. Kwong, T. Lam, L. Lang, C. Medri, A. Murchison, S. Russell, U. Stahmer, E. Sykes, J. Villagran, A. Vorauer, T. Wanne and T. Yang
Company: Nuclear Waste Management Organization
Date: March 2011

This report is a summary of progress in 2010 for the Nuclear Waste Management Organization's (NWMO's) Technical Program. The Technical Program is supporting implementation of Adaptive Phased Management (APM), Canada's approach for long-term management of used nuclear fuel.

Significant technical program achievements in 2010 include:

- The NWMO Independent Technical Review Group (ITRG) held their third annual review of the NWMO technical program. The ITRG report noted significant development in the NWMO's technical program since 2008 and indicated that the program covers a full range of scientific and technical topics that are relevant to the current stage of APM implementation. NWMO prepared an action plan addressing the recommendations of the ITRG report. The ITRG 2010 report and NWMO action plan are available on the NWMO website.

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

- NWMO provided research contracts and research grants to 13 Canadian universities and, as an approved industrial partner with the Natural Science and Engineering Research Council of Canada, supported 6 postgraduate scholarships in 2010.

- NWMO's research program published 22 NWMO technical reports and 14 peer-reviewed journal articles.

- NWMO conducted research on: used fuel container corrosion; repository sealing material development and repository design. NWMO also continued to develop a repository monitoring and retrieval program and continued to survey developments in used fuel reprocessing and alternative waste management technologies.

- NWMO continued to refine engineering conceptual designs, cost estimates, transportation logistics and implementation schedules in support of APM.

- In May 2010, NWMO issued "*Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel*" which describes the site selection process and the proposed site evaluation criteria to ensure safety of people and the environment.

- The NWMO geoscience program continued to develop plans and methods for detailed site investigations in the fields of: geochemistry; radionuclide transport properties; microbiology; geomechanics; seismicity; and hydrogeology. NWMO also continued to develop numerical modelling methods and continued to assess long-term geosphere stability associated with glaciation, seismicity and deep groundwater flow systems.

- NWMO continued to maintain and improve models and data suitable for supporting the safety assessment of potential sites and designs. In 2010, safety assessment models assessing the used nuclear fuel waste form, deep geological repository, generic geosphere and surface biosphere were improved, integrated and maintained.

- In 2010, the glaciation scenario postclosure safety case was published as two NWMO technical reports (TR 2010-09 and TR-2010-10). The study indicates that potential releases from a deep geological repository would remain well below regulatory limits even when the glaciation effects are considered. In addition, work on preparing the "Fourth Case Study" assessing the postclosure safety of a deep geological repository at a hypothetical site in crystalline rock continued and two preclosure studies were initiated to examine aspects of conventional and public radiological safety at the facility.

ABSTRACT

Title: **THE EFFECT OF CANDU FUEL BUNDLES ENDPLATE/ENDCAP WELD MORPHOLOGY ON COMPUTED STRESS INTENSITY FACTORS AT THE WELDS**
Report No.: **NWMO TR-2011-03**
Author(s): Bogdan S. Wasiluk
Company: Kinectrics, Inc.
Date: April 2011

Delayed hydride cracking has been identified as a potential degradation mechanism of the endplate-to-endcap assembly welds in CANDU fuel bundles during long-term dry storage. Consequently, in order to assess whether DHC is a concern, the stress intensity factor for DHC initiation of Zircaloy endplate-to-endcap assembly welds needs to be established. This parameter will be used in deterministic and probabilistic assessments of the structural integrity of the fuel bundles.

This report discusses the effects of fuel element and endplate geometry, weld morphology and endplate-to-endcap weld on computed stress intensity factors. The stress intensity factors were computed from the *J*-integral or *I*-integral using the finite element method. The stress intensity factors for mode I, II and III loading were also determined in order to investigate the deformation of the crack front.

Results from this investigation led to the following conclusions:

- The calculated stress intensity factors show a strong dependence on circumferential extension of an endplate-to-endcap weld discontinuity up to a ninety degree from the top of the weld. Beyond the ninety degrees, the susceptibility is less pronounced.

- The shape of the endplate-to-endcap weld discontinuity, round versus elliptical, was found to play a minor role in the representative depth of the endplate-to-endcap weld discontinuity.

- Deformation of the endplate significantly changes distribution of stresses at the endplate-to-endcap weld discontinuity.

- The maximum value of stress intensity factor could be re-located from the vertical plane to a plane at forty five degree from the vertical for a GE-1 type fuel element.

- The position of the endcap regarding to the endplate strongly affect stress intensity factors. The maximum value of the stress intensity factor could be moved from the plane at forty five degree to the vertical plane because of it.

- Uncertainties in characterization of the endplate-to-endcap weld discontinuity leads to considerable error in the calculated stress intensity factor.

- An endplate-to-endcap weld discontinuity could be under complex combined modes I, II and III crack loading during both experiment and during fuel bundle storage.

ABSTRACT

Title: **USED FUEL INTEGRITY PROGRAM: SUMMARY REPORT**
Report No.: **NWMO TR-2011-04**
Author(s): Jose Freire-Canosa
Company: Nuclear Waste Management Organization
Date: February 2011

When CANDU fuel bundles are removed from a nuclear reactor, they are stored on an interim basis in wet storage bays for a period of about seven to ten years and then transferred to licensed dry storage facilities at the reactor site while awaiting the development of a deep geological repository for long-term management. The majority of used fuel in dry storage in Canada is in the Dry Storage Containers (DSCs) developed by Ontario Power Generation.

During the period of dry storage, several mechanisms such as creep rupture, stress corrosion cracking and delayed hydride cracking could potentially affect the integrity of the CANDU fuel bundles. The Used Fuel Integrity Program was established in 2004 to improve our understanding of processes that could affect fuel bundle integrity and to assess whether those processes pose a risk of mechanical failure of the fuel bundles in dry storage. The most important threat to CANDU fuel bundle integrity was found to be Delayed Hydride Cracking (DHC) of the endplate/endcap welds which could lead to mechanical failure of the bundle welds.

This report provides a summary of the Used Fuel Integrity Program and the key findings of the work. A Finite Element Model (FEM) of the CANDU fuel bundle was developed and tested to predict fuel bundle stress fields following its post-in-reactor life. The “Bundle Stress Model” was created with the ANSYS code as a parametric model which allows for ease of simulating various fuel bundle load conditions and bundle deformations. Solutions obtained with the model were verified against test measurements of the deformations experienced by unirradiated commercial bundles subjected to various load conditions. Loads applied to the fuel bundles tested covered both linear elastic and plastic stress regimes. The Bundle Stress Model provided excellent trending of the data and good reproducibility of the test data.

Concurrent with the development of the Bundle Stress Model, laboratory experiments were done with unirradiated endplate/endcap welds from artificially hydrided CANDU fuel bundles to hydrogen levels of 40-60 ppm. The intent was to obtain a database of threshold stress intensity factors (K_{IH}) which would lead to DHC failure of the welds. The values of this database were then used to compare against the stress intensity factors expected to be operative at the welds as estimated from the field stresses calculated with the “Bundle Stress Model”.

The results of this evaluation indicate that maximum stress intensity factors of the order of 3 MPa $m^{1/2}$ are expected for 28-element Pickering type CANDU fuel bundles when radiation effects are factored in. The database from the experimental program indicates that the threshold stress intensity factor for DHC crack initiation is in the range 7.6 to 13.6 MPa $m^{1/2}$. Therefore, DHC is not projected to occur and the bundles are expected to retain their integrity during dry storage. Similar results are expected for the 37-element Bruce type CANDU fuel bundles.

ABSTRACT

Title: **STATUS REPORT ON THE STRESS CORROSION CRACKING BEHAVIOUR OF OFP COPPER IN NITRITE AND AMMONIA SOLUTIONS**
Report No.: **NWMO TR-2011-06**
Author(s): C.D. Litke[1] and B.M. Ikeda[2]
Company: [1] Atomic Energy of Canada Ltd.
[2] University of Ontario Institute of Technology
Date: February 2011

This report covers a series of corrosion studies performed in 2009 and 2010, which were undertaken to enhance the understanding of the role of stress corrosion cracking (SCC) agents, particularly nitrite and ammonia, in the stress corrosion cracking (SCC) behaviour of oxygen-free phosphorous-doped (OFP) copper. In a deep geological repository (DGR), these SCC agents could be present as a result of microbial activity, blasting, or radiolysis of moist air. The studies investigated the effects of (i) nitrite and ammonia concentrations, (ii) nitrite/chloride and ammonia/chloride concentrations, (iii) copper concentration, and (iv) applied current on the SCC behaviour of OFP Cu. Constant extension rate tests (CERTs) were performed at room temperature using a compact tension specimen. The findings are summarized as follows:

- SCC was evident in a range of deaerated nitrite concentrations between 0.1 $mol \cdot L^{-1}$ and 1.0 $mol \cdot L^{-1}$, at an applied current density of 1 $\mu A \cdot cm^{-2}$. Lower concentrations of nitrite (≤0.01 $mol \cdot L^{-1}$) appeared to be insufficient to induce SCC.
- With nitrite concentration ≥ 0.1 $mol \cdot L^{-1}$, a 1:1 chloride to nitrite concentration ratio suppressed SCC, as did an overabundance of chloride. High chloride concentrations appeared to increase uniform corrosion, which coincided with a blunting of the crack tip.
- In a deaerated 0.1 $mol \cdot L^{-1}$ nitrite solution, the susceptibility to SCC appeared to decrease with increasing chloride concentration, and increase with increasing applied current density (0.01 $\mu A \cdot cm^{-2}$ to 1 $\mu A \cdot cm^{-2}$).
- Steady-state potential values became more negative with increasing chloride concentration regardless of the nitrite concentration.
- SCC was evident in a range of ammonia concentrations between 0.3 $mol \cdot L^{-1}$ and 1.0 $mol \cdot L^{-1}$, while a concentration of 0.1 $mol \cdot L^{-1}$ ammonia did not induce SCC. A concentration of 0.3 $mol \cdot L^{-1}$ ammonia appears to approach the threshold concentration required for SCC.
- In a 1.0 $mol \cdot L^{-1}$ ammonia solution, a 1:1 chloride to ammonia concentration ratio suppressed SCC, as did an overabundance of chloride. The addition of chloride in concentrations ≤0.5 $mol \cdot L^{-1}$ had little effect on SCC.
- In a 0.5 $mol \cdot L^{-1}$ ammonia solution, a 1:1 chloride to ammonia concentration ratio appeared to enhance SCC. The addition of 0.7 $mol \cdot L^{-1}$ chloride did not bring about SCC suppression.

In nitrite solutions a 1:1 chloride to nitrite concentration ratio is sufficient to suppress SCC. However in 0.5 $mol \cdot L^{-1}$ ammonia, SCC was not suppressed at that concentration ratio. The body of results from the ammonia work suggest that there may be a threshold concentration of 1.0 $mol \cdot L^{-1}$ chloride required for SCC suppression rather than a concentration ratio.

ABSTRACT

Title: **FAR-FIELD MICROBIOLOGY CONSIDERATIONS RELEVANT TO A DEEP GEOLOGICAL REPOSITORY – STATE OF SCIENCE REVIEW**
Report No.: **NWMO TR-2011-09**
Author(s): Barbara Sherwood Lollar
Company: University of Toronto
Date: December 2011

This report presents a state of science review of international literature and knowledge on the role of microorganisms in relation to the key issues affecting the design and performance of a deep geological repository (DGR) for used nuclear fuel, with a focus on far-field microbial processes. The report draws on peer-reviewed scientific literature, publically available reports from nuclear waste management programs both internationally and in Canada, and from relevant microbiological investigations in the resource sector. The report is aimed at those who are familiar with the area of long-term nuclear waste management, but who are not experts in microbiology and the geochemistry of the subsurface.

The literature for international programs on far-field microbiology, as reviewed in this report, typically reported several general findings:

1. It is recognized that indigenous microbes exist in a broad range of geologic environments and it cannot *a priori* be assumed that a subsurface geologic environment is sterile.
2. The review of international programs shows that microbiological characterization programs can be integrated with the geologic/hydrologic/geochemical investigations to ensure feedback between these approaches.
3. The presence, diversity and activity of indigenous microbial populations in the far-field is controlled by a number of factors, including principally: geologic (physical) and chemical (including mineralogical) properties of the host rock; transport properties of the host rock; geochemistry of the associated groundwater; hydrogeologic properties; and both geologic and geochemical history and evolution of the site.
4. Hydrology, geochemistry and resident microbial populations may be sensitive to changes or perturbations in the system. Many systems possess geochemical buffering capacity to counter the effects of perturbations.
5. Microbiological far-field investigations should incorporate techniques that eliminate, to the degree possible, any contamination due to sampling/drilling, but should also control for contamination by characterizing not only the indigenous geochemistry and microbiology, but also the geochemical and microbiological properties of any potential contaminant end-members.

ABSTRACT

Title: **SORPTION EXPERIMENTS IN BRINE SOLUTIONS WITH SEDIMENTARY ROCK AND BENTONITE**
Report No.: **NWMO TR-2011-11**
Author(s): Peter Vilks, Neil H. Miller and Kent Felushko
Company: Atomic Energy of Canada Limited
Date: December 2011

This report summarizes the results of an experimental program investigating sorption processes in Na-Ca-Cl brine solutions with Canadian sedimentary rocks and bentonite. Protocols for batch sorption tests with Na-Ca-Cl brine solutions were first developed. These included guidelines for experimental configurations, solid/liquid ratios, phase separation methods and sorption time scales. The sorption of Sr(II), Ni(II), Cu(II), Eu(III) and U(VI) was then characterized on bentonite, shale and limestone in Na-Ca-Cl brine solutions with total dissolved solid (TDS) values as high as 300 g/L.

Strontium did not sorb in brine solutions, indicating that sorption coefficients for group 1 and group 2 elements, such as Ra(II), should be assigned values of 0. In contrast, transition metals, such as Ni and Cu, and the trivalent Eu and hexavalent U sorb by surface complexation mechanisms to bentonite, shale and limestone in brine solutions. The sorption of Ni and Cu increased with pH increases from 6 to 8, while the effect of pH on Eu and U sorption was not clear. The high concentrations of Ca in the brine competed with Ni for sorption sites. The formation of complexes with carbonate reduced the sorption of Eu and U. Although Ni sorption was 70 to 90 percent complete after 1 week, Ni continued to sorb at a slow rate and probably did not reach steady-state until after 4 weeks. The sorption of Eu and U appeared to reach a steady-state after 1 to 2 weeks, although Eu sorption on limestone may have continued for longer than 4 weeks in some cases. The sorption of U appeared to be reversible over a several week period, but the sorption of Ni and Eu was not reversible within a two week period.

On the basis of these experiments, preliminary recommendations for sorption coefficients applicable to sedimentary rocks are suggested.

ABSTRACT

Title: **SORPTION OF SELECTED RADIONUCLIDES ON SEDIMENTARY ROCKS IN SALINE CONDITIONS – LITERATURE REVIEW**
Report No.: **NWMO TR-2011-12**
Author(s): Peter Vilks
Company: Atomic Energy of Canada Limited
Date: December 2011

Sedimentary rocks in Canada, including shales and limestone, are considered as potentially suitable host rock types to host a deep geologic repository. Some of these rocks are known to contain Na-Ca-Cl brine solutions with total dissolved solids (TDS) of up to 375 g/L. The sorption properties of these rocks and the clay based sealing materials (eg.bentonite) in the repository need to be evaluated if contaminant sorption (in the geosphere and repository) is to be included in the safety assessment calculations for the repository. The international literature and sorption databases were searched to find sorption data that would be relevant to Canadian sedimentary rocks (shale and limestone) and bentonite, in a setting that would include Na-Ca-Cl brine solutions at near neutral pH. Redox conditions were factored for those elements that are redox sensitive. The elements of interest included C, Cu, As, Se, Zr, Nb, Mo, Tc, Pd, Sn, Pb, Bi, Ra, Th, Pa, U, Np, Pu and Am. Sorption data relevant to brine solutions were found for bentonite, shale, limestone, illite, chlorite and calcite for some, but not all, elements. Where possible, chemical analog considerations were used to fill data gaps. From these data a set of recommended sorption values was identified for bentonite, shale and limestone. These values are intended as a starting point for the development of a Canadian sorption database for sedimentary rocks.

ABSTRACT

Title: **MODELLING REACTIVE TRANSPORT IN SEDIMENTARY ROCK ENVIRONMENTS – PHASE II, MIN3P CODE ENHANCEMENTS AND ILLUSTRATIVE SIMULATIONS FOR A GLACIATION SCENARIO**
Report No.: **NWMO TR-2011-13**
Author(s): Sergio Andres Bea Jofré[1], K. Ulrich Mayer[1] and Kerry T. B. MacQuarrie[2]
Company: [1]Department of Earth and Ocean Sciences, University of British Columbia
[2]Department of Civil Engineering, University of New Brunswick
Date: December 2011

Canada's plan for the long-term care of used nuclear fuel is containment and isolation in a Deep Geologic Repository (DGR) constructed in a suitable sedimentary or crystalline rock formation. In sedimentary basins fluid migration and geochemical conditions may be impacted by multiple interacting processes including density-dependent groundwater flow, solute transport, heat (energy) transport, mechanical loading, and rock-water interactions. Understanding the interactions among these processes is important when assessing the long-term hydrodynamic and geochemical stability of sedimentary basins during glaciation/ deglaciation events. To improve the capability to investigate these processes, an enhanced version of the reactive transport code MIN3P (i.e., MIN3P-NWMO) was developed and tested. The key code enhancements included: fluid density and activity coefficient formulations for high ionic strength solutions; inclusion of one-dimensional hydromechanical coupling to account for fluid pressure changes due to ice sheet loading; and coupling with heat (energy) transport. The new capabilities of MIN3P-NWMO were verified and tested for selected problems by making comparisons with the results of other similar models and available analytical solutions.

ABSTRACT

Title: **STATUS OF CORROSION STUDIES FOR COPPER USED FUEL CONTAINERS UNDER LOW SALINITY CONDITIONS**
Report No.: **NWMO TR-2011-14**
Author(s): Gloria M. Kwong
Company: Nuclear Waste Management Organization
Date: June 2011

Copper has been studied as a corrosion resistant material for used fuel containers in the Canadian nuclear waste management program. Over the past 20 years, many studies have been carried out on the corrosion behaviour of copper under anticipated low salinity conditions (< 60 g/L [Cl^-]) that could be found in a deep geological repository in crystalline rock. The subject of copper corrosion has also been extensively studied in the Swedish and Finnish nuclear waste management programs as copper is also specified in their canister designs. This report summarizes the state of understanding of the long-term behaviour of copper under low salinity conditions from these studies and what the implications are for the predicted service life of the container in a deep geological repository. The key findings include:

- Copper will corrode under atmospheric conditions (at a relative humidity > 50-70%) and the rate and mechanism of corrosion will be affected by the presence of atmospheric contaminants.
- A copper used fuel container in a deep geological repository will experience an initial short period of uniform corrosion leading to some surface roughening under aerobic conditions, but once long-term anaerobic conditions are established, it will become thermodynamically stable in the absence of sulphide.
- Stress corrosion cracking on a copper used fuel container is unlikely due to the lack of:
  (i) the required threshold concentration of stress corrosion cracking agents;
  (ii) a suitable interfacial pH, and
  (iii) the required corrosion potential on the copper surface. The elevated Cl^- and initially the elevated temperature will also lower the probability of stress corrosion cracking.
- Microbiologically influenced corrosion is expected to be controllable through the use of compacted bentonite to suppress microbial activity in the near field.

The knowledge gained over the past 20 years from studies on the corrosion of copper has allowed predictions of the lifetime of a copper used fuel container in a deep geological repository. Under low salinity groundwater conditions, a realistic estimate of copper corrosion from all processes is about 1.27 mm in 1 million years in a deep geological repository.

Therefore, the lifetime of a copper used fuel container is expected to exceed 1 million years in a deep geological repository in crystalline rock. This finding is consistent with the predicted container lifetime for the Swedish deep geological repository in crystalline rock.

ABSTRACT

Title: **TWO-COMPONENT SWELLING TESTS OPERATED FOR THREE, NINE AND TWENTY-SEVEN MONTHS**
Report No.: **NWMO TR-2011-15**
Author(s): C-S. Kim and D. Priyanto
Company: Atomic Energy of Canada Limited
Date: January 2011

The Backfilling and Closure of the Deep Repository (BACLO) project was a co-operative international effort that involved a variety of activities supported by SKB and Posiva, as well as a limited scope of in-kind contributions from Nuclear Waste Management Organization (NWMO). This project ended in 2009 and was superseded by the BASE (Backfill and Sealing) project, which continued the work begun prior to that date. From 2008 onwards the contribution from NWMO to this work involved laboratory tests that have been done for NWMO by Atomic Energy of Canada Limited (AECL) to examine the mechanical (strain) interactions between dissimilar components of the clay-based sealing system. Specifically, this ongoing work has been investigating the manner in which water supplied from the rock will be taken up by densely compacted backfill blocks and bentonite pellets configured to represent the tunnel fill in a placement room of a deep geological repository using the In-Floor Borehole placement method.

In this testing program, a total of 17 testing cells were installed at AECL's geotechnical laboratory in order to examine the process of water uptake and volumetric equilibration of backfill clay blocks in contact with clay pellets. These tests consisted of two different assemblies (i.e., Friedland clay blocks-bentonite pellets and Asha clay blocks-bentonite pellets) and two different groundwater compositions (1.0% and 3.5% of 50% Sodium Chloride (NaCl) and 50% of Calcium Chloride ($CaCl_2$) by mass). The replicated cells were scheduled to be dismantled at intervals of 3, 9 and 27 months with associated measurement of gravimetric water content and volume changes of the components installed (expansion or compression).

This report presents a summary of the results obtained by dismantling the test cells after 3, 9 and 27 months of operation. Data obtained during dismantling include measurement of the distribution of internal gravimetric water content and density, as well as a measure of how these change with time. The test results show that a system consisting of two similar mineralogical materials, will come to a homogeneous density state and two different pore fluid salinities (1.0% and 3.5%) had little effect on the apparent rate of system equilibration. This information will be useful to provide a means of better understanding the role of both time and groundwater salinity on the short-term evolution of clay-based sealing materials.

ABSTRACT

Title: **ENVIRONMENTAL RADIOACTIVITY IN CANADA - MEASUREMENTS**
Report No.: **NWMO TR-2011-16**
Author(s): S.C. Sheppard, B. Sanipelli
Company: ECOMatters Inc.
Date: May 2011

A recent review of background concentrations of radionuclides in surface waters and soils across Canada identified gaps in information. In particular, there were few data for ^{129}I and ^{36}Cl. Additionally, the degree of disequilibria in U and Th decay series was not well characterised. The present project involved sampling of 21 surface waters from New Brunswick to Saskatchewan. Analysis of ^{129}I and ^{36}Cl was by Accelerator Mass Spectroscopy and U and Th progeny by radiochemical methods. Trace elements and tritium were also measured. The observed concentrations of ^{129}I, ^{36}Cl and ^{3}H were consistent with expectations, and the present study increased by several fold the numbers of data available for Canadian waters. Concentrations of ^{232}Th, ^{235}U and ^{238}U were detectable in all locations, with substantial ranges. The U and Th decay series radionuclides were seldom detectable in water. Data were obtained for ^{129}I and several U and Th decay series radionuclides in a few soil and rock samples.

ABSTRACT

Title: **REVIEW OF ENVIRONMENTAL RADIOACTIVITY IN CANADA**
Report No.: **NWMO TR-2011-17**
Author(s): S.C. Sheppard, M.I. Sheppard, B. Sanipelli
Company: ECOMatters Inc.
Date: May 2011

The objective was to review and summarize background concentrations of radionuclides in surface water and soil across Canada. Three types of radionuclides were considered. The first radionuclides were primordial, including parents and progeny of ^{235}U, ^{238}U and ^{232}Th, ^{40}K and ^{97}Rb. The second were rare but naturally occurring radionuclides of special interest, including ^{3}H, ^{14}C, ^{36}Cl and ^{129}I. The third were fallout radionuclides with emphasis on ^{3}H, ^{14}C, ^{137}Cs and ^{90}Sr. Data were obtained specifically for Canadian sites, but included data from international sources as needed. Contaminated sites were avoided, but associated control-site data were evaluated. The temporal domain was present-day, but with attention to any potentially important trends, notably time since atmospheric nuclear bomb testing. In addition to the background radionuclide concentrations, Environment Increments were also identified that are one geometric standard deviation above the background geometric mean value.

ABSTRACT

Title: **ESTIMATE OF INSTANT RELEASE FRACTIONS USING ORIGEN-S AND FEMAXI**
Report No.: **NWMO TR-2011-19**
Author(s): F. Iglesias, M. Kaye, and B. Lewis
Company: Candesco Corporation, University of Ontario Institute of Technology, and Royal Military College of Canada
Date: December 2011

The purpose of this work was to determine conservative yet realistic estimates of the fractions of used fuel radionuclide inventories that are available for instant release upon simultaneous breach of the fuel sheath and saturation of a used fuel container. The estimates were obtained by using ORIGEN-S to calculate the radioactive inventory of ten spent CANDU fuel bundles at discharge while FEMAXI V6.1 was used to calculate the Instant Release Fractions (IRFs) at the grain boundary and fuel-to-sheath-gap. The IRFs were successfully calculated and compared with a set of experimental results (Stroes-Gascoyne, 1996). Additional estimates were performed for four fuel bundle conditions, representing average and pessimistic conditions.

Chemical speciation calculations were carried out using the pessimistic case (a bundle power of 900 kW and a bundle burnup of 320 MWh/kgU) since it yielded higher inventories for the radionuclides of interest. The results of these calculations show the chemical speciation of the radionuclides in the gap and grain boundaries and their amounts for the most important compounds; specifically, volatile species, soluble fission products in the UO_2 fuel, the solid solution U(Pd-Rh-Ru)3, noble metals inclusions (Mo, Rh, Pd, Ru, Tc) in BCC and HCP crystallographic form, and other solid and liquid compounds.

ABSTRACT

Title: **SYVAC3-CC4 THEORY**
Report Number: **NWMO TR-2011-20**
Company: Nuclear Waste Management Organization
Date: June 2011

This report describes the theory for the Canadian Concept Generation 4 (CC4) system model for postclosure safety assessment of a deep geologic repository for used CANDU fuel. The system model is composed of several linked submodels – the wasteform and containers, the engineered barriers in the repository, the geosphere, and the biosphere.

The CC4 model was developed to address the configuration of a deep geologic repository for used nuclear fuel with emplacement of durable containers, surrounded by dense clay and backfill. The repository is located deep underground in stable, saturated rock. The submodels of the wasteform, containers and engineered barriers describe the failure of some containers through small defects, degradation of the used fuel, contaminant (radionuclide) release through the defects in the container, and migration of contaminants through buffer and backfill materials. The geosphere model describes the movement of contaminants from the repository via the groundwater in both the rock mass and in the fracture system, to the surface environment. The biosphere model describes the movement of contaminants between surface water, soils, atmosphere, vegetation, animals and humans, and the consequent radiological dose to a reference person and generic biota living near the repository.

Earlier versions of this system model were used for the case studies presented in the AECL Environmental Impact Statement and Second Case Studies, in the OPG Third Case Study, and in the NWMO Glaciation Study. This report describes Version CC4.08 of the system model.

ABSTRACT

Title: **SYVAC3-CC4 USER MANUAL**
Report No.: **NWMO TR-2011-22**
Author(s): C.I. Kitson, T.W. Melnyk, L.C. Wojciechowski, T. Chshyolkova
Company: Atomic Energy of Canada Limited
Date: June 2011

CC4 (Canadian Concept generation 4) is a system model for the release and transport of radionuclides from a deep geologic repository. It includes a vault, a local geosphere, and the biosphere in the vicinity of any surface discharge zones. It is integrated with the SYVAC3 executive (System Variability Analysis Code) and the Modelling Algorithm Library (Version ML303) to form the reference Canadian postclosure safety assessment computer code. The version described here is SCC408, based on SYVAC3.12 and CC4.08.

The vault code simulates the following processes: random failure of containers through small defects; release of contaminants from UO_2 fuel, Zircaloy fuel sheaths, other metal wasteforms, or soft wasteforms to the interior of a failed container, including a radiolysis-based fuel dissolution model; precipitation of contaminants inside a failed container if solubility limits are exceeded, including calculation of solubility limits from groundwater composition for Np, Pu, Tc, Th and U; transport by diffusion of dissolved contaminants through the defect in the failed container to enter the surrounding buffer; transport by diffusion, advection and sorption of contaminants through the buffer, backfill and excavation damaged zone into the surrounding host rock using a nested-cylinder geometry; division of the vault into sectors, with release calculated from each sector into the local geosphere; and linear decay chains.

The geosphere model simulates the following processes: ability of the aquifer to provide water to a well; effect of the well pumping on the groundwater flow; diffusive and advective transport of contaminants in groundwater; converging and diverging flow paths; spatial variation in transport properties from segment to segment along the transport pathway, including linear equilibrium sorption and colloids; capture of contaminant plume by the well; and linear decay chains. The geosphere can have up to 10 unique states varying with time; for example, glaciation cycles. The geosphere transport can also be replaced by links to calculations conducted externally using, but not limited to, FRAC3DVS.

The biosphere model simulates the following processes: contaminant release into aquatic or terrestrial discharge zones; collection of all contaminants into a lake; concentrations of contaminant in the lake water, lake sediments, and in the surface soil of a garden, forage field, woodlot, and peat bog; contaminant concentrations in the air (indoor and outdoor); loss of radionuclides from the biosphere by radioactive decay, discharge from the lake, and burial into deep lake sediments; internal and external radiation exposures to members of a self-sufficient human household living in the area and using contaminated water, foods and materials; and internal and external radiation exposure to representative nonhuman biota. The biosphere model can contain up to four unique biospheric states, i.e. glaciation cycles (temperate, permafrost, ice sheet, and proglacial lake).

Mass accumulation and distribution is calculated in the models for the intact containers, failed containers, vault engineered barriers, geosphere and biosphere.

This manual describes the CC4 capabilities, limitations, execution, inputs and outputs, error and warning messages, and other information needed to run the model.

ABSTRACT

Title: **NUCLEAR FUEL WASTE PROJECTIONS IN CANADA – 2011 UPDATE**
Report No.: **NWMO TR-2011-25**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2011

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

The important technical features of these recent nuclear initiatives include:

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

This report updates the 2010 report (Garamszeghy, 2010) and summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2011 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. The report focuses on power reactors, but also includes prototype, demonstration and research reactor fuel wastes held by AECL.

As of June 30, 2011, a total of approximately 2.3 million used CANDU fuel bundles (approx 46,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 77,000 bundles (approx 1,500 t-HM) from the 2010 report. For the existing reactor fleet, the total projected number used fuel bundles produced to end of life of the reactors ranges from about 3.0 to 5.3 million used CANDU fuel bundles (61,000 t-HM to 107,000 t-HM), depending upon decisions to refurbish current reactors. The lower end is based on an average of 25 effective full power years (EFPY) of operation for each reactor (i.e. no refurbishment), while the upper end assumes that reactors are refurbished and life extended for an additional 25 EFPY of operation. This is increased slightly from the 2010 report due to change in life assumptions.

Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the NWMO has assumed a reference projected used fuel inventory of 4.6 million CANDU fuel bundles.

Used fuel produced by potential new-build reactors will depend on the size and type of reactor and number of units deployed. New-build plans are at various stages of development and the decisions about whether to proceed with individual projects, reactor technology and number of units have not yet been made. If all of the units where a formal licence application has already been submitted are constructed, the total additional quantity of used fuel from these reactors could be up to approximately 1.6 million CANDU fuel bundles (30,000 t-HM), or 10,800 PWR fuel assemblies (5,820 t-HM). This total is has been reduced from the 2010 report due to the formal withdrawal of some new-build licence applications by the proponents.

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

ABSTRACT

Title: **SEISMIC ACTIVITY IN THE NORTHERN ONTARIO PORTION OF THE CANADIAN SHIELD: ANNUAL PROGRESS REPORT FOR THE PERIOD JANUARY 01 – DECEMBER 31, 2010**
Report No.: **NWMO TR-2011-26**
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Geological Survey of Canada
Natural Resources Canada
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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 2010.

CHIS maintains a network of eighteen 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 CHIS network of temporary stations at: Sutton Inlier (SILO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Experimental Lake (EPLO), Pickle Lake (PKLO), Pukaskwa National Park (PNPO), Aroland (NANO), and Timmins (TIMO). The digital data from a temporary station at Victor Mine (VIMO), supported 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.

During 2010, 118 events were located. Their magnitude ranged from 0.7 m_N to 3.2 m_N. The largest events included a m_N 3.2 in the Atikokan region, ON and two m_N 3.1 near Sultan, ON. The most westerly event in the area being studied was a m_N 1.9, located 113 km northeast of Gimli, MB. The 118 events located in 2010 compares with 82 events in 2009, 114 events in 2008, 68 events in 2007 and 83 events in 2006.