Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2012

NWMO TR-2013-01

September 2013

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ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2012**
Report No.: **NWMO TR-2013-01**
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Abstract
This report is a summary of activities and progress in 2012 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 2012 are summarized below.

- 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 11 Canadian universities, 3 foreign universities and supported 6 postgraduate scholarships in 2012 as an approved industrial partner with the Natural Science and Engineering Research Council of Canada.

- NWMO's research program published 21 NWMO technical reports and submitted 12 abstracts for presentation at international conferences focused on environmental radioactivity and radioactive waste management.

- NWMO continues to pursue engineering conceptual designs, canister and emplacement designs, cost estimates, transportation logistics and implementation schedules in support of APM. A redesign of Used Fuel Packing Plant systems was initiated in 2012 to assess the impact of a reduced size used fuel container.

- NWMO continued to develop a repository monitoring and retrieval program, and continued to review developments in used fuel reprocessing and alternative waste management technologies. The NWMO continues to conduct research on used fuel container corrosion, as applicable to the potentially high salinity bedrock of Canada. The NWMO has initiated experiments for 2013 that are comparable to the high salinity copper corrosion experiments carried out in Sweden.

- 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, radionuclide transport, microbiology, geomechanics, seismicity, long term geosphere stability and hydrogeology. NWMO continued to develop and sponsor modelling and analytical methods that will be used to assess long-term geosphere performance. New

research programs to develop methodologies for age-dating of minerals within fractures or vein and for the identification of paleoseismic events were initiated.

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

- NWMO concluded work on an illustrative case study investigating the postclosure behaviour of an APM deep geological repository situated at a hypothetical crystalline site. NWMO initiated work in 2012 on an illustrative case study to investigate the postclosure behaviour of an APM deep geological repository situated at a hypothetical sedimentary site

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM) for the 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 (DGR) in order to ensure continuous improvement and consistency with international best practice. Examples of conceptual designs for a DGR are illustrated in Figure 1.1 and Figure 1.2.

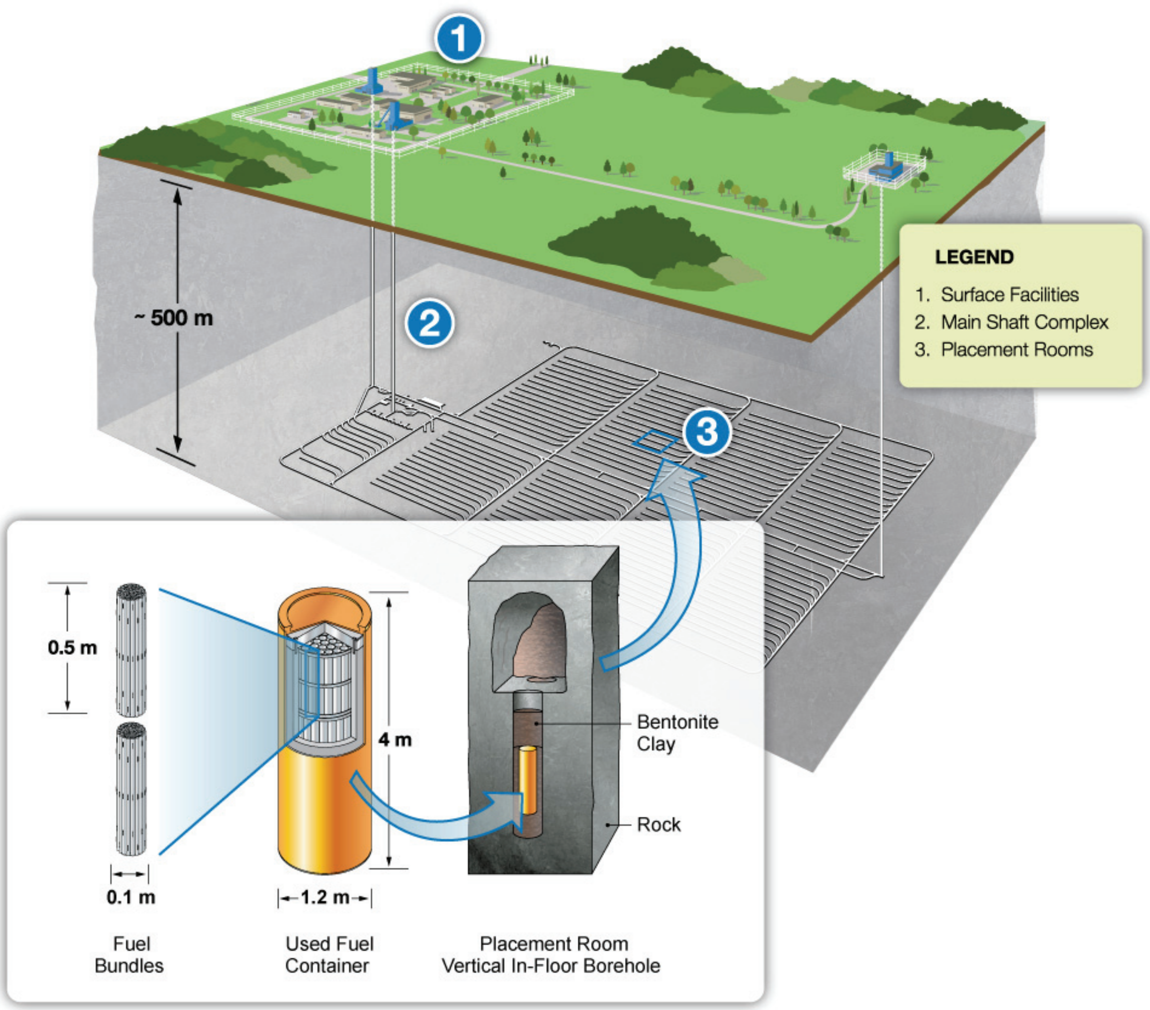

Figure 1.1: Illustration of a Deep Geological Repository – In-floor Borehole Placement

Work conducted and progress made within the APM Technical Program during 2012 is summarized in the remainder of this report. A brief update on the status of NWMO's site selection process is provided below.

1.1 SITE SELECTION PROCESS

On September 30, 2012, the NWMO suspended accepting new expressions of interest from potential host communities. A total of 21 communities have passed the initial screenings (Step 2). 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 consists of the following: a) initial screenings to evaluate the suitability of candidate sites against a list of preliminary 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 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.

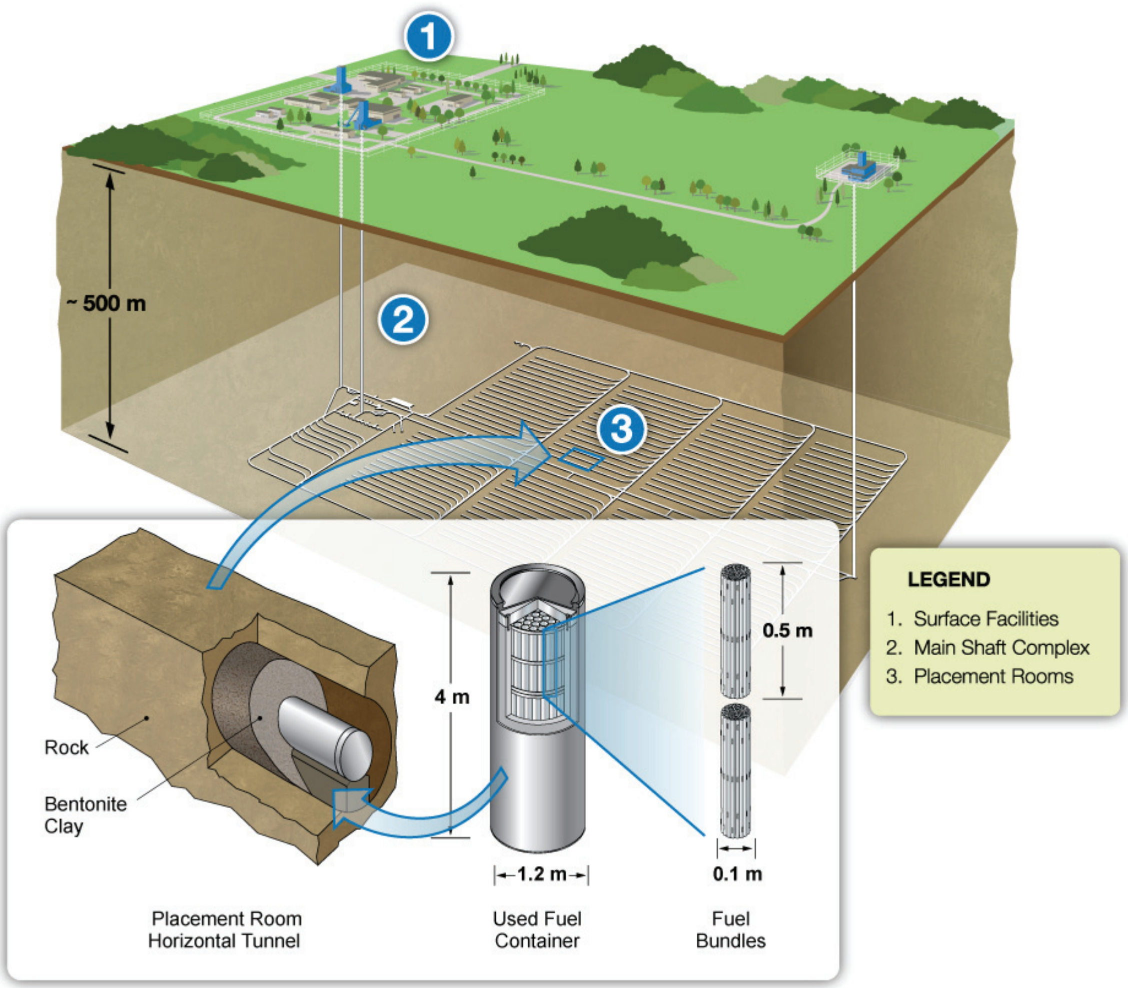

Figure 1.2: Illustration of a Deep Geological Repository – Horizontal Tunnel Placement

NWMO completed initial screenings for ten communities in 2012 and moved on to feasibility studies in preparation for completing all initial screenings in 2013. The initial screening reports are published on NWMO's site selection website (http://www.nwmo.ca/sitingprocess). In 2013, the NWMO will initiate feasibility studies for those communities that have decided to move onto this next step in the site selection process.

2. Overview of Canadian Research and Development Program

2.1 REGULATORY FRAMEWORK

Nuclear facilities in Canada, 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 agreed to 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 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 and are broken down into 4 groups.

A: Complete illustrative repository safety assessments.

1. Prepare illustrative pre-project safety analyses for reference repository designs in crystalline and sedimentary rock settings.

2. Provide Regulatory Affairs support for Canadian Nuclear Safety Commission, pre-project review of illustrative repository safety analyses and APM repository licensing.

B: Optimize repository engineered systems and designs.

3. Complete optimization and proof testing of generic repository engineered systems and designs by 2019.

C: Build confidence in the deep geological repository safety case.

4. Further increase confidence in the safety case for a DGR.

5. Enhance scientific understanding of processes that may influence DGR safety.

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

D: Provide technical assessment support to APM siting process.

7. Conduct geoscientific and biosphere characterization to support selection and licensing of a preferred repository site.

A list of the technical reports produced by NWMO in 2012 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 2011 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, Kennell et al., 2012). 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 programs.

2.3 SUMMARY OF INTERNATIONAL ACTIVITIES

An important aspect of the NWMO's technical program is collaboration and interaction 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 the sharing of lessons learned in repository technology development and site characterization. In 2012, NWMO continued to participate in the following work programs at the Äspö HRL:

- LASGIT (LArge Scale Gas Injection Test), and
- Engineered Barrier System Modelling Task Force.

NWMO is a partner in the Mont Terri Project, which consists 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. During the current phase of the Mont Terri Project (Phase 18, July 2012 to June 2013), NWMO is involved in the following experiments:

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

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 2012, the fourth and final full season of the GAP project was completed, which included a geochemical sampling program of surface water bodies and a pingo. Radar surveys, and the drilling of boreholes through the ice to the ice-bed interface, concluded in 2012. Planning is underway for comprehensive final reporting, detailing the results of the four-year field campaign and the associated data and modelling interpretations. Final reports (Volume 1 and 2) are projected for publication in 2014-2015.

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;
- GSC 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 2012, two projects receiving financial support from the NWMO were completed, including:

- Interpretation of results of dose assessments for non-human biota, and
- Dose to intruders arising as a result of drilling.

For 2013, the NWMO is contributing to the funding of three projects as part of BIOPROTA:

- C-14 Project,
- Non-Human Biota Temporal and Spatial Scales Project, and
- Geosphere-Biosphere Interface Project.

These projects are financially supported by the NWMO in partnership with ANDRA and EDF (France), BfS (Germany), EPRI (USA), Nagra and ENSI (Switzerland), NDA RWMD (UK), NUMO (Japan), POSIVA (Finland), and SKB and SSM (Sweden).

2.4 INDEPENDENT PEER REVIEW

The APM Technical Program is reviewed annually by the Independent Technical Review Group (ITRG). In September 2012, the ITRG held their fourth meeting with the NWMO. They reported their findings and recommendations to the NWMO Board of Directors in November 2012. The ITRG 2012 Report and associated NWMO Action Plan can be found on the NWMO website at http://www.nwmo.ca/itrg.

3. REPOSITORY ENGINEERING

Within the Repository Engineering program, active research and development continued during 2012 on: used fuel recovery and transport; the used fuel container and its potential for corrosion; the used fuel packing plant; buffer and sealing systems; and, development of underground placement concepts. Summaries of these activities are provided in the following sections.

3.1 USED FUEL RECOVERY AND TRANSPORT

3.1.1 Used Fuel Logistics Study

A review of the potential options for used fuel recovery from wet/dry storage and transport to a DGR was completed in 2012. The study identified that the NWMO's generic reference design, which envisions used fuel storage in modules and road transport within a Used Fuel Transportation Package (UFTP), provided an optimum approach for fuel recovery and transport to a DGR. Also identified as potential options for fuel recovery were:

- Rail transport of Dry Storage Containers, and
- Road transport of Dry Storage Baskets within a Used Fuel Transportation Package.

These additional fuel recovery options will be further studied prior to preparation of the construction license package.

3.1.2 Preliminary Waste Acceptance Criteria

The NWMO has authored and maintains Waste Acceptance Criteria (WAC). The WAC establishes fundamental requirements for acceptance of the used fuel for transportation and emplacement within the DGR. The WAC has been updated to incorporate the additions of the Used Fuel Logistics Study (Section 3.1.1; rail transport of dry storage containers and road transport of dry storage baskets within a used fuel transportation package).

3.1.3 Transportation Cost Model

In 2009, a macro-level computer model was developed to project the cost of operating a used fuel transportation program over the course of 38 years. The model projects costs to a hypothetical site using a singular set of assumptions. NWMO enhanced the model capabilities in 2012 to include: the ability to input different fuel inventory numbers, designation of numerous destination sites or host communities, adjustments to fleet size, variances to the number of shipments, and changes to estimated travel time and distances.

3.1.4 Transportation Dose Report

In order to implement a used fuel management program, the fuel will be required to be transported from interim storage sites to a repository. In order to assess any potential dose to the public from this transportation process, NWMO prepared a generic dose study using the

Used Fuel Transportation Package (Batters et al., 2012). Three scenarios were selected to represent the bounding parameters for the most likely pathways from which the public could receive exposure from the UFTP:

1. Individuals living and or working along a transportation route;
2. Drivers and passengers in vehicles sharing the roadway with the UFTP; and
3. Persons stopping at a rest centers at the same time as the UFTP vehicle.

NWMO also included a fourth scenario addressing exposure to the public in the event of an accident involving the UFTP transport vehicle. In all cases, the dose to the public from the UFTP was calculated to be orders of magnitude below the legal limit set by the Canadian Nuclear Safety Commission (CNSC), and was found to be lower than the amount of exposure received from everyday natural sources, such as the sun.

3.2 USED FUEL CONTAINER (UFC)

3.2.1 Used Fuel Container Development

NWMO continues to consider alternative Used Fuel Container (UFC) design concepts, which include a copper-steel dual-vessel and a steel-only vessel. The selection of the final container design will be dependent, in part, on the repository geology and geochemical environment. The reference UFC concept is based on a large capacity vessel holding 360 used fuel bundles.

As part of the 2012 Repository Engineering program, efforts to assess UFC design alternatives were continued, leading to the completion of several key engineering and manufacturing technology programs. This included the completion of:

- A detailed UFC Sizing Study, assessing both manufacturability and cost implications of 20 different UFC sizes/geometries/capacities; and,
- Technical feasibility programs evaluating copper coating technologies for the direct application of the corrosion barrier to the exterior surface of the steel core (as an alternative to the reference wrought copper–steel vessel design).

Data from these programs is being utilized in the further assessment of UFC design options considering the contribution of repository interfacing systems (Used Fuel Packaging Plant, DGR design, and UFC placement). A decision on an optimum UFC design, based on all factors, is expected in 2013. Technical specifications will be developed, and prototypes manufactured, for performance testing in subsequent years. The structural performance of the UFC will be modeled by design and stress analysis and verified by physical integrity testing (external pressure testing) under expected service conditions. In 2012, a structural analysis of a candidate UFC design was performed via the development of a mechanical integrity model utilizing advanced Finite Element Analysis. The results were presented in a preliminary design report that was reviewed by external experts, and a formal technical report will be prepared to summarize the findings.

In parallel to design activities, continuing experimental efforts were carried out in 2012 in order to increase knowledge about important corrosion characteristics for both UFC material options as they relate to the long-term performance of the container under expected repository conditions. Details of these work programs are described in subsequent sections of this report.

3.2.2 Used Fuel Container Corrosion Studies

3.2.2.1 Corrosion of Copper

As identified previously by NWMO and other organizations, copper materials are expected to be very long-lived within the DGR environment. NWMO is investigating the effects of copper corrosion within potentially highly saline groundwater, consistent with observations of water chemistry in many Canadian sedimentary or deep crystalline environments. In these groundwater environments, total dissolved chloride can exceed 3 mol/L and early container temperatures may approach 100°C. Under these salinity and temperature conditions, thermodynamic calculations have revealed that copper may be susceptible to anaerobic (i.e., oxygen-free) corrosion, as per equation 1.

$$Cu + nCl^- + H_2O \rightarrow CuCl_n^{(1-n)} + \tfrac{1}{2}H_2 + OH^- \qquad (1)$$

Within equation 1, the value n can, in principle, be either 2 or 3, and the presence of this anionic species is why the corrosion process may proceed. Calculations within NWMO's Corrosion of Copper Program, initiated in 2011, have revealed that greater than 80% of the chloride containing species above 2.5 mol/L chloride is in the form $CuCl_3^{2-}$. Within the on-going work, which involves very sensitive hydrogen measurements over several months, corrosion processes have been observed to occur very slowly. Corrosion rates on the order of 2-4 nm/y are measured at temperatures above 75°C, in the pH range of 4 to 5.5 and at 5 mol/L chloride. Decreasing the temperature to room temperature (i.e., approximately 20-25°C) reduces hydrogen generation below the detection limit, which is approximately a factor of 10 below the measured values (i.e., 0.2 nm/y). In the absence of clay barriers and bedrock associated with the geosphere, which would restrict movement of water toward and movement of corrosion products away from the container, a corrosion rate of 4 nm/y for 100,000 years would result in 0.4 mm of copper corrosion in bulk, highly saline solution at temperatures above 75 °C. In the presence of the mass-transfer limiting clays and rock formations, corrosion rates would be expected to be significantly reduced.

Although evidence exists that copper is long-lived in anaerobic conditions, Swedish researchers have demonstrated that copper corrosion may proceed for extended periods of time in pure water, and in the absence of oxygen, as per equation 2, to produce a copper hydroxide-containing species, as well as hydrogen gas:

$$Cu + H_2O \rightarrow CuOH_n^{(1-n)} + \tfrac{1}{2}H_2 \qquad (2)$$

Unlike the copper chloride-containing species described in equation 1, the copper hydroxide species proposed by Swedish researchers (Szakálos et al., 2007) is not expected by conventional thermodynamic analyses. NWMO will initiate experiments in 2013 that are comparable to the high salinity copper corrosion experiments described above in order to assess corrosion of copper in pure water. Although results are not available at this point, NWMO anticipates that any corrosion that may occur by this process will be lower than the amount expected for the high chloride solutions; thus, the NWMO copper corrosion allowance will account for processes described by both equations 1 and 2.

NWMO has undertaken work to provide extensive updates to models that describe copper corrosion within the repository as a whole, such that the models can be adapted to the commercially available program, COMSOL Multiphysics. A final report detailing this work will be produced in 2013.

NWMO has conducted an extensive review of the copper corrosion allowance first presented in TR-2011-14 (Kwong, 2011). For this process, NWMO is working with copper corrosion experts who have not been previously involved in DGR research and whose focus has been on copper corrosion within infrastructure (i.e., plumbing, drinking water, etc.). Over the second half of 2012, NWMO provided extensive documentation of historical programs on copper corrosion, and met with experts to provide detailed program descriptions and to identify any shortcomings in future work packages. A technical report was independently produced, verifying the suitability of the NWMO corrosion allowance of 1.27 mm over one million years, and this report will be available in 2013.

3.2.2.2 Corrosion Testing of Copper

Prior to its implementation as a corrosion barrier, a copper coating must be demonstrated as suitably corrosion resistant. Significant historical effort has been directed at assessing copper as a corrosion barrier and NWMO has designed programs that compare copper coatings to conventional, wrought copper specimens. To date, NWMO has performed 3 month exposure testing of copper coatings, where oxygen content has ranged from low (i.e., experiments conducted in a glove box) to high (i.e., solutions purged with oxygen). Measurements of the electrochemical potential have revealed that the copper coatings behave similarly to the wrought copper specimens. In addition, post-exposure analysis has not resulted in any differentiation among the copper-coated and wrought copper components. On-going investigations include longer exposures, as well as exposures of the various samples to humid air, solutions of different salinity, and different temperatures. In addition, inter-granular corrosion will be investigated through accelerated corrosion tests that do not simulate the DGR environment, but may serve to identify regions within the copper coating that are more susceptible to corrosion processes. This work is expected to last until 2015 and will gradually be expanded to include any possible corrosion processes, such as those described for copper in high salinity solutions and in pure water (Section 3.2.2.1).

3.2.2.3 Corrosion of Steel

NWMO has undertaken the task to update models that describe steel corrosion within a repository so that the COMSOL Multiphysics code, which is used to assess copper corrosion (see Section 3.2.2.1), can be used for the purposes of assessing steel corrosion as well. A technical report (King and Kolar, 2012), which documents the simulation of anaerobic corrosion for steel-only used fuel containers, predicts container lifetimes between 11,200 and 36,500 years with corrosion allowances of 1 cm and 3 cm The results are consistent with assessments from nuclear waste organizations internationally, as well as previous work done for NWMO. A technical report will be produced in 2013 that describes the lifespan assessment of steel-only containers.

In a DGR, hydrogen can be generated through anaerobic corrosion of steel, which can then diffuse into the steel. To address this issue, experimental studies are being carried out to investigate the susceptibility of carbon steel and welded steel (with different metallurgical and mechanical properties) to hydrogen embrittlement. In 2012, hydrogen absorption and permeability studies were carried out in moist nitrogen, dry hydrogen, and moist nitrogen/hydrogen environments. The findings indicate that the amount of hydrogen in the molecular form that can be absorbed, and which can then diffuse into the steel, is greatly suppressed by the air-formed iron oxide on the steel surface. In 2013, wedge opening loading (WOL) tests will be carried out to investigate the embrittlement susceptibility of steel materials in both wet and dry hydrogen environments. The intent of this program is to identify the acceptable range of hardness that exists in UFC steels/weldments, for which hydrogen induced cracking does not occur, under a variety of heat treat conditions. The results of this program are expected in 2013.

3.2.3 Used Fuel Container Closure Weld Development

NWMO is currently investigating an alternate, one-piece, UFC design concept that would be closed and sealed by a weld and then copper coated. The current two-piece NWMO reference UFC consists of a steel inner vessel with a bolted lid and an outer wrought copper shell.

The closure welding operation of the UFC is critical and presents various process/inspection challenges due to the radioactive nature of the container load. The closure welding process must be suitable for remote welding operation using an automated or remotely controlled system in a radioactive environment. The welding process must also be designed to achieve the hardness restriction and required impact toughness without post-weld heat treatment.

In 2012, two studies were commissioned to investigate the technical feasibility for partial penetration closure welds of the one-piece concept. The welding processes, weld joint design and weld quality will be evaluated and verified through metallurgical examination, non-destructive examination (NDE) by ultrasonic techniques, and mechanical testing. These studies will be completed in 2013.

3.2.3.1 Hybrid Laser Arc Welding

The Hybrid Laser Arc Welding (HLAW) process is a combination Laser Weld and Gas Metal Arc Weld (GMAW) process. Preliminary HLAW test results have indicated that high quality single-pass 10-mm-deep and 19-mm-deep closure welds can be achieved without the need for post-weld heat treatment so long as samples have been pre-heated to 400°C. The weld test samples meet hardness, impact toughness and tensile strength requirements, and are equivalent to the base material properties. Further evaluations, including residual stress profiling and non-destructive examinations, will be carried out on weldments applied to both flat and cylindrical sections of steel. Figure 3.1 is a cross-section of a typical HLAW weld and illustrates the microstructure obtained by this process.

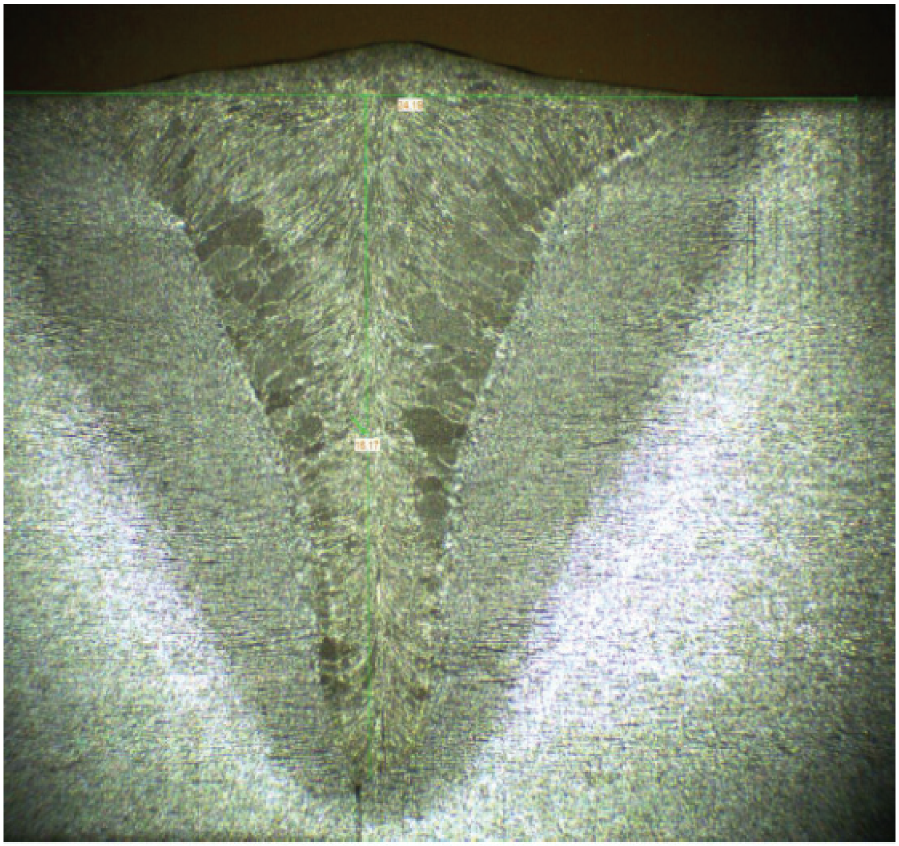

Figure 3.1: Macrograph Cross-section of a Typical 10 mm penetration Hybrid Laser Arc Weld Showing the Weld Fusion and Heat Affected Zone (5.6x magnification)

3.2.3.2 Friction Stir Welding

Friction Stir Welding (FSW) is a weld technology that has shown great promise in recent years with soft metals. The FSW process is a solid state joining process that produces a high quality weld. FSW is being investigated as a possible technique for the UFC closure weld and a study was commissioned by NWMO late in 2012. The initial tests will involve 10-mm-deep welds on samples of flat steel, and may be extended to include testing on round sections of steel.

3.2.4 Used Fuel Container Copper Coating Development

One of the major research areas for NWMO in 2012 was the manufacturing of a suitable copper corrosion barrier for the UFC. While the two-piece inner steel and outer copper container in the reference container design offers a viable option for producing a suitably corrosion resistant UFC, manufacturing challenges exist for its production (specifically, the required tight tolerances between the steel and copper vessels). A gap of less than 1 mm between the outer copper shell and the inner steel vessel over the entire length is required to overcome creep-related fracture. Accordingly, NWMO has been investigating the concept of applying a copper coating or cladding directly onto the steel container. There are several advantages to this over an outer wrought copper shell. By coating the container, copper creep is not possible. Such a copper layer could be engineered to the appropriate thickness to meet its purpose of corrosion protection (i.e., a few mm), which would reduce container weight, cost, and potentially simplify container handling, both above and below ground. NWMO has investigated three coating methods and these are described below.

3.2.4.1 Electrodeposition

As a commercialized process, electrodeposition offers the advantage of coating production on a large scale; however, it is usually used for thin (< 0.5 mm) coatings, owing to deposition rates that are generally below 1 mm/h. On a small scale, this can translate to as little as a few µg/h; however, for the large surface area of a UFC, deposition rates can exceed many tens of kg/h. Within the NWMO program, copper coatings in excess of 3 mm on steel substrates were produced. These proved to:

- Have no porosity, as measured via surface analysis;
- Contain very little oxygen (< 50 ppm);
- Be ductile, with elongations in excess of 20%;
- Be well adhered to the steel, as measured via bend testing; and
- Contain very little hydrogen.

On-going work involves assessing the capability of electrodeposition to produce coatings on curved, welded or tortuous surfaces, as will be required for UFCs. In addition, quantifying the adhesion of these coatings will be a part of future work.

3.2.4.2 Cold Spray

Cold spray involves the acceleration of powders to high velocity within an inert carrier gas. When the powders impact a substrate at high velocity a mechanical bond is formed. While very high deposition rates can be obtained by a single gun (i.e., up to 1 kg/min), it has been primarily used to-date as a repair process within industry. Within the NWMO program, both low pressure cold spray (LPCS) and high pressure cold spray (HPCS) have been investigated for both complete UFC coverage and coating repair.

Among the cold spray programs, LPCS was revealed to be the poorest performer for complete UFC coatings. In addition to possessing lower deposition rates than HPCS, the formation of thick (i.e., > 1 mm) copper coatings proved to be impossible using LPCS in the absence of aluminum/alumina bonding layers. The method has proven to be suitable for coating repairs when used on intentionally damaged samples. The portability of the equipment, when compared to HPCS, makes LPCS an attractive option for repair processes.

HPCS was examined over two studies that focused on a range of topics. In addition to assessing a range of readily available commercial powders for the process, the work programs investigated substrate pre-conditioning, post-deposition heat treatments, and damage/repair processes. The most effective means of applying the coating was shown to involve the sequential use of two carrier gases. Initially, a helium carrier gas produces a well bound layer of fewer than 100 µm, followed by the use of a nitrogen carrier gas to thicken the coating to approximately 3 mm. Following deposition, material properties of the optimized coatings were determined and were found to be of low porosity (i.e., <0.1%). The as-deposited coatings proved to be sufficiently hard, with low elongation (i.e., < 2%); as a result, these could be fractured during bend tests. Once partial (i.e., 300°C) or full (i.e., 600°C) annealing was performed of the coatings, significant ductility was obtained. Greater than 15% and 35% elongations were measured for coatings heated to 300°C and 600°C, respectively.

As a result of these investigations, reference coating deposition and heat treatment parameters were developed that will be applied to samples with curved, welded or tortuous surfaces as part of future work.

3.2.4.3 Laser Deposition

One of the first copper coating programs NWMO initiated was based on laser deposition, whereby low-oxygen copper powder was heated to melting by a laser, and then deposited onto a steel substrate. This process proved to be ineffective for copper powders because the high reflectivity of the copper resulted in the dissipation of heat and reduced deposition efficiency. A secondary program has been initiated utilizing laser cladding of copper wire, for which higher deposition rates are expected.

3.2.4.4 Non-Destructive Examination (NDE) of Copper Coatings

As part of the coating development program, NWMO has initiated Non-Destructive Examination (NDE) as a means of assessing coating integrity. For copper cold spray samples, NDE was successfully utilized to verify intact, non-porous coatings, as well as to characterize a naturally occurring defect within a coating. When the surface is polished, it is possible to observe defects in the coating smaller than 0.5 mm using phased array analysis, and the minimum defect size in the preliminary work is smaller than 1 mm. Within on-going programs, transducers that can withstand radiation fields will be used and NWMO will begin the process of creating a defect library. The NDE program will include aspects of the welding program as well because similar radiation fields will be present during weld analysis. Defect size tolerances from welds will be similar to those defined for the copper coatings.

3.3 USED FUEL PACKING PLANT (UFPP)

The reference design for the UFPP remains unchanged for 2012. Conceptual screening work was initiated in 2012 to assess the impact of a reduced size UFC on the UFPP. The study will provide an assessment of the changes required to the UFPP in order to meet the throughput requirements of 120,000 used fuel bundles in 48-bundle capacity UFCs. This work will be completed in 2013.

3.4 BUFFER AND SEALING SYSTEMS

In 2012, NWMO continued to assess the properties of bentonite-based sealing materials through laboratory studies. The work program included: consolidation and triaxial testing; bentonite component swelling studies; an assessment of as-placed bentonite pellets; and, a literature review on the addition of graphite to the buffer. 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,
- Gap Fill (GF) – 100% bentonite clay fabricated in the form of dense pellets.

In 2012, a long-term triaxial testing and consolidation program continued to assess the properties of a 70/30 bentonite sand mix (70/30BF). This work is underway in the geotechnical laboratories at both the Royal Military College of Canada and the University of British Columbia.

A joint international project was carried out to advance the repository design for the placement of bentonite pellets in the gap and void space surrounding used fuel containers and placement rooms (Kim et. al., 2012). In an effort to optimize the physical and thermal properties of bentonite pellets, a series of practical laboratory tests using a bentonite pellet-making apparatus were conducted. A total of 56 batches of pellets were made for the study, representing a range of pellet sizes and shapes, as well as the effects of various volumetrically inert fillers on the properties of bentonite-based materials.

The pellets were assessed primarily to evaluate the potential for improving their density, strength, durability, and heat transfer capability. Several different swelling clay materials of interest to NWMO, SKB and Posiva were examined, as well as mixtures of bentonite with illitic clay or fine silica sand. Filler contents of 10, 25, and 50% by weight were tested. The addition of Wyoming bentonite fines (i.e., 80 mesh granules), vibrated into the pore space between the pellets, was undertaken to evaluate their effect on overall density and thermal characteristics of the gap fill. The fines typically resulted in improved as-placed dry density (>1.5 Mg/m^3). The vibration of Wyoming bentonite fines generally provided a slight improvement to the thermal conductivity of the pellet fill materials. The maximum thermal conductivity values measured on pellets that were densified by this vibratory compaction method were approximately 0.6 W/(m·K).

3.4.1 Microbial Studies of Repository Sealing Systems

The NWMO near-field microbiology program assesses the presence and diversity of microorganisms in the engineered barrier system (EBS), with the objective of identifying and testing design provisions that can inhibit microbial activity. Over the last 20 years, there have been significant advances in subsurface microbiology in the context of a DGR for used nuclear fuel. In 2012, a state-of-knowledge review summarizing microbiological considerations relevant to a DGR for used nuclear was prepared by Ryerson University and the University of Saskatchewan (Wolfaardt and Korber, 2012). The report summarizes microbiology research that has been conducted, both in Canada and internationally, relating to the prevalence and survival of microorganisms as a function of environmental conditions (e.g., radiation, temperature, water activity, nutrient availability, salinity) and the physical constraints imposed by bentonite buffer designs (e.g., swelling pressure, pore size). Potential impacts of microorganisms on the integrity of the bentonite buffer and used fuel containers (i.e., as a result of microbially-influenced corrosion) are also summarized.

The review points out that the potential for microbial activity in low-permeability crystalline and sedimentary host rock formations is low, and that, realistically, metabolic activity scarcely meets requirements for cell preservation, let alone proliferation. Through time, it is likely that microbial populations and activity will return to those levels of the surrounding host rock environment. As such, the relevant questions are: i) to what extent will biotic reaction rates increase as a consequence of the disturbances that would accompany construction of a DGR, and ii) how long will it take for microbial rates to return to the original levels? Based on these questions, and the recommendations in the report (Wolfaardt and Korber, 2012), three new work programs were initiated in 2012 to: 1) further evaluate microbial activity in the EBS, and in particular, interfaces between various components (University of Saskatchewan and Ryerson University); 2) determine nutrient and organic carbon sources and availability in bentonite materials considered for use in a DGR (University of Toronto); and 3) model biogeochemical and hydrogeological processes in a DGR for used nuclear fuel (University of Toronto). The programs will collaboratively identify and test DGR design and operation procedures that minimize microbial activity in the DGR.

Throughout 2012, NWMO continued to support and contribute to the Hydrogen Transfer (HT) and Microbial Activity (MA) experiments in the Mont Terri Underground Rock Laboratory. These experiments evaluate potential biogeochemical processes in the repository environment. Preliminary results from the HT experiment, suggest that hydrogen disappeared twenty times faster than would be expected considering dissolution and diffusion alone in a pulse release (Visnot et al., 2012). Similar results were observed following hydrogen injection over a period of more than six months using semi-continuous injection (Visnot et al., 2012). Current work focuses on modeling the fate of released hydrogen and evaluating the role that microorganisms may have in its attenuation. In 2012, NWMO also funded participation of University of Saskatchewan microbiologists in an inter-laboratory sample analysis program. Opalinus Clay core samples were sent to four different microbiology labs to assess indigenous microbial communities in the potential Swiss host rock environment. Participation of University of Saskatchewan researchers in this exercise will benchmark Canadian methods that will be used to evaluate microorganisms in bentonite clay proposed in Canadian DGR designs.

3.5 SITE AND REPOSITORY

The NWMO continued to develop underground placement concepts in 2012 through numerical modeling and laboratory experiments. The work included: the optimization of the underground layout for a single and double level repository for the in-floor borehole concept in a crystalline geosphere; development of underground repository concepts for a 48-bundle used fuel container; and, a limited assessment of an alternative excavation method.

In 2011, the Adaptive Phased Management (APM) conceptual design and cost estimate was updated for a deep geological repository in crystalline rock for a base case inventory of 3.6 million used CANDU fuel bundles and an alternate case inventory of 7.2 million used CANDU fuel bundles (SNC-Lavalin Nuclear Inc., 2011a and 2011b). The fuel age is assumed to be 30 years out-of-reactor. The APM repository was assumed to be located on a single level at a depth of 500 m.

In 2012, thermal-mechanical (TM) numerical modeling was used to optimize the spacing of the used fuel containers within a placement room and the spacing of the placement rooms in a repository constructed in a hypothetical crystalline rock geosphere. The analysis of a unit cell of the repository (centreline to centreline of placement rooms, and centreline to centreline of containers) showed that at a depth of 500 m, and for a fixed distance of 4.2 m between containers, the placement rooms can be spaced at 25 m centreline to centreline without the peak temperature of the surface of the containers exceeding 100°C (Carvalho and Steed, 2012a). A thermo-mechanical analysis was then used to optimize the placement room spacing based on an alternate inventory of 7.2 million used CANDU fuel bundles placed in two repository levels in the hypothetical crystalline rock geosphere (Carvalho and Steed, 2012b). Through thermo-mechanical analysis of a unit cell of the repository (centreline to centreline of placement rooms, and centreline to centreline of containers), with the repository at depths of 400 m and 800 m, with a fixed distance of 4.2 m between containers, the placement rooms can be spaced at 36 m centreline to centreline without the peak surface temperature of the containers exceeding 100°C. Alternatively, the placement rooms can be spaced at 32 m centreline to centreline in the upper level and 38 m centreline to centreline in the lower level without the peak temperature of the containers exceeding 100°C. This optimized spacing of the placement rooms results in a footprint of 2 km × 1.45 km for both levels using the same spacing in both levels. Using the a different room to room spacing in each level, the footprint of the multiple level repository would be 2 km × 1.5 km for the lower level and 2 km × 1.3 km for the upper level.

As a component of the on-going APM development program, opportunities exist to optimize the design of the APM Deep Geological Repository in terms of the container design, placement method and underground layout. Alternative used fuel containers have been designed specifically for the CANDU used fuel bundles in order to improve handling and to develop a commercially optimum DGR concept. In 2012, conceptual placement room designs were developed for smaller, 48- and 76-bundle used fuel containers. These containers are significantly smaller than the 360 bundle IV-25 used fuel container that was described in the 2011 design and cost update (SNC-Lavalin Nuclear, 2011a, 2011b). Conceptually, the alternative used fuel containers would be surrounded by a highly compacted bentonite overpack, as shown in Figure 3.3. The resulting “super container” would be assembled in the used fuel packaging plant, and then transported underground to the placement room. In this concept, the room is a drill and blast excavated opening that has a slightly larger cross-sectional area than the two transversely stacked super containers. An illustration of the placement of the lower super container is shown in Figure 3.4.

An expert review was carried out on the in-room placement concept for the smaller sized containers. It was concluded that the concept is technically feasible as a repository method and meets the high demands of operational and long-term safety requirements. It was pointed out that water inflow into the placement room would need to be accounted for in order to develop a robust method, and further development would be required in establishing: 1) methods for smooth rock blasting (in crystalline rock); 2) design and manufacturing of the bentonite buffer around each used fuel container; 3) more rigid confinement of the super container; 4) the filling of the gap between the super container and rock wall; and, 5) the design of the pellet bed beneath the super container.

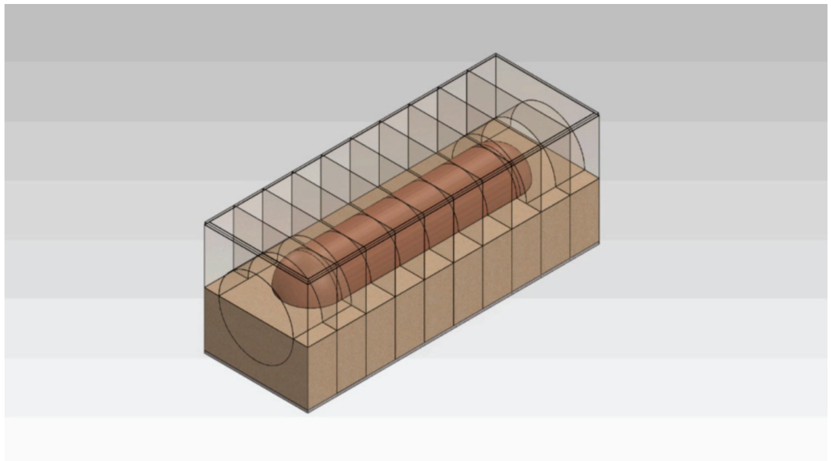

Figure 3.2: Illustration of 12FB-4L - 48 Used Fuel Bundle Container Surrounded by HCB Over-pack

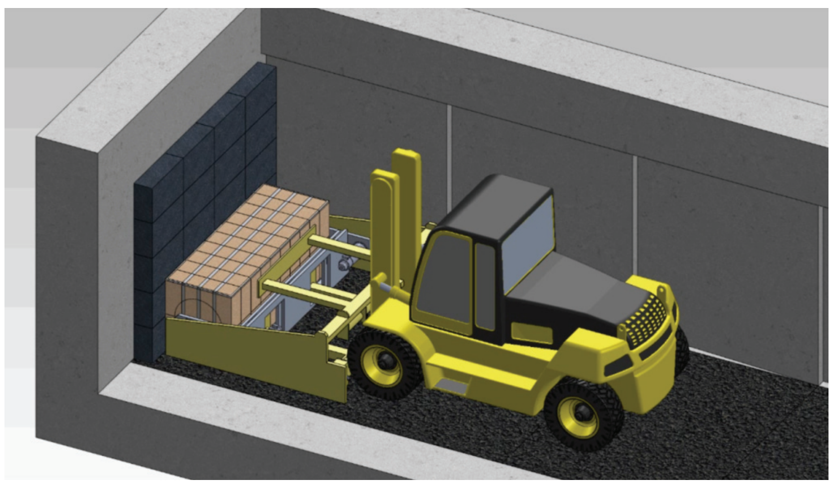

Figure 3.3: Illustration of the 12FB-4L UFC Being Placed on a Thin Leveling Layer in the Placement Room

4. GEOSCIENCE

In collaboration with technical experts, both in Canada and internationally, the NWMO is pursuing an on-going geoscience research program addressing a wide range of 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 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. 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 2012.

4.1 GEOSCIENTIFIC SITE CHARACTERIZATION

In 2012, NWMO continued to develop geoscience work programs focused on the development and refinement of methods for site characterization activities, including microbiology (Section 4.1.1), paleoseismicity (Section 4.1.2), petrophysics (Section 4.1.3), radiometric dating (Section 4.1.4) and geochemistry (Section 4.2). These programs continued to improve modelling, experimental, and environmental monitoring capabilities, as are required for the purposes of assessing flow system evolution (Section 4.3), long-term geosphere stability (Section 4.4), and geomechanical properties of the rock mass (Section 4.5). New in 2012 was the initiation of fracture mineral age-dating and fluid inclusion temperature studies, with both areas of research offering new and more powerful ways of characterizing site history and geological evolution. Many of the methods being developed are unique to the NWMO requirements of investigating deep aquicludes.

4.1.1 Microbiology Site Characterization Methods

The objective of the far-field microbiology program is to prepare for site characterization activities associated with siting a DGR for used nuclear fuel. In 2012, research activities focused on the development of microbial biomass extraction methods from low-permeability sedimentary rock for deoxyribonucleic acid (DNA) analysis and phospholipid fatty acid (PLFA) analysis by the University of Toronto in collaboration with the Desert Research Institute and McMaster University. Extraction of DNA from subsurface microbial communities can, for example, be confounded by the presence of organic matter and clay materials, which complex and co-extract with the nucleic acids and interfere with nucleic acid purification due to their strong binding tendencies (Mauclaire et al., 2007; Poulain et al., 2008). Previous NWMO research assessing microbial communities in two low-permeability sedimentary rock formations (Queenston Formation shale and Cobourg Formation limestone) using PLFA, neutral lipid fatty acids (NLFA) and diglyceride fatty acids (GLFA), as well as cultured in both dilute growth media and media, indicated some viable microorganisms (and larger numbers of dead cells) were found in the shale samples. In contrast, results for the limestone samples were consistent only with contamination by common aerobes during drilling or sample handling. Culture results indicated the presence of common non-halophilic, mostly facultative anaerobic spore formers, but the indigenous nature of these organisms remains to be investigated (Stroes-Gascoyne and Hamon, 2008). In 2013, the DNA analysis methods developed for analysis of low-permeability rock will be applied to the Queenston Formation shale and Cobourg Formation limestone to benchmark the methods against the previous investigation (Stroes-Gascoyne and Hamon, 2008).

4.1.2 Paleoseismicity

In 2012, NWMO joined an on-going Paleoseismicity study within the Ottawa-Bonnechere Graben that is being conducted by the Geological Survey of Canada (GSC) (Figure 4.1).

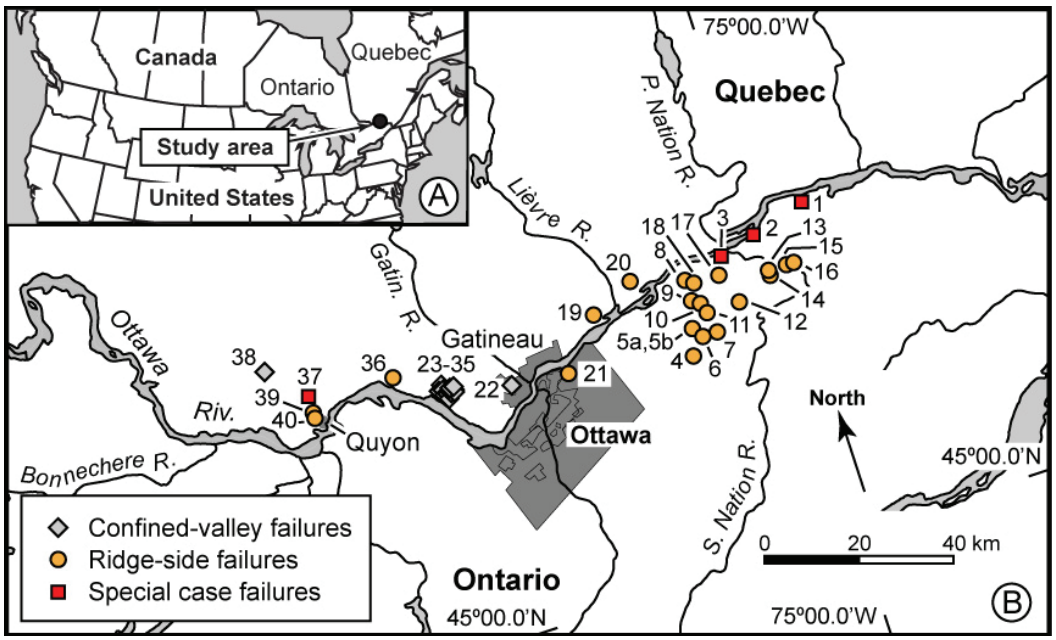

Figure 4.1: A) Inset Map Showing the General Location of the Ottawa Valley Study Area in Eastern Canada; B) Locations of the 41 Dated Landslide and Disturbed Terrain Sites within the Ottawa Valley with Each Classified in the Confined-valley, Ridge-side or Special Case Groups; Symbol Size Does not Reflect the Feature Scale

This work program relates to several important issues with respect to APM DGR siting, site characterization and safety case development, including: 1) extension of the existing seismic activity record beyond that currently available (ca. 160 years); 2) improved understanding of earthquake frequency and magnitude following ice-sheet retreat; 3) provide improved seismic data to substantiate assessment and influence of earthquakes in a DGR safety case (i.e., Seismic Hazard Assessment); and 4) provide additional data to assess geosphere stability as it relates to engineered barrier system performance and far-field barrier integrity. This project will be summarized in a technical report in 2014.

4.1.3 Determination of Petrophysical Properties

To aid in refinig an understanding of mass transport properties of in low-porosity rocks, NWMO introduced a new petrophysical research program in 2011. Petrophysical analysis provides a means to directly or indirectly determine the parameters that influence pore fluid and mass transport – particularly porosity, permeability and pore fluid saturation – within both sedimentary and crystalline environments. The objective of this new research program 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.

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. Core samples collected from Ordovician sedimentary units in a borehole 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 included measurement of Total Organic Carbon content, Rock-Eval Pyrolysis, and bulk and clay-size fraction determination using X-Ray Diffraction. A final report documenting the results is expected in 2013.

4.1.4 Radiometric Age Determination of Fracture-Infilling Mineral Phases

A key issue in the long-term safety assessment of a DGR is the need to demonstrate an understanding of the geological evolution of the potential host rock mass during the period of time for which repository performance must be evaluated. Mineral-filled fractures and openings (e.g., veins and vugs) in a rock mass provide evidence that fluid migration events have occurred at some point in the geologic past. Vein and vug emplacement may be related to diagenesis (in sedimentary rocks), orogenic activity and/or uplift and erosion. Characterization of the infilling mineral phases, including absolute age determinations of the in-filling material, can provide useful information regarding the tectonic history of the rock mass, geologic stability and fluid migration events.

As part of the broader study of fracture characterization, a program involving radiometric Uranium-Lead (U-Pb) age analysis of vein calcite was initiated at the University of Toronto's Jack Satterly Geochronology Laboratory. An important component of the work program involves development of a methodology to extract reliable absolute ages of calcite mineral growth using a comparative analysis of Laser Ablation-Inductively Coupled Mass Spectrometry (LA-ICPMS) and Isotope Dilution-Thermal Ionization Mass Spectrometry (ID-TIMS) techniques. While this work program is focused on vein calcite in sedimentary rocks, it is envisaged that the methods and interpretative strategy developed will be suited to both sedimentary and crystalline rock environments.

The first stage of the project involved an assessment of the radiogenic character (U and Pb isotope concentrations) of each calcite vein sample using LA-ICPMS with the understanding that only the most radiogenic samples would be suitable for precise age determination by ID-TIMS. Data on ^{206}Pb, ^{207}Pb and ^{238}U was collected to provide age information. A sample subset, with well defined LA-ICPMS ages, was chosen for comparative ID-TIMS analyses.

Fracture-infilling calcite from the Ordovician carbonate samples yielded Paleozoic ages that overlap with the deposition age of the host rocks (ca. 445 +/- 42 Ma). Surface and core samples from the Devonian Lucas Formation yielded Late Cretaceous to early Paleogene ages, with two well-defined peaks at ca. 110 and 56 Ma, that are interpreted to represent the timing of fracturing and fluid migration events. LA-ICPMS and ID-TIMS ages for both age peaks in the Devonian samples overlapped within their respective error ranges. This highlights the consistency between ages determined using the LA-ICPMS and ID-TIMS and suggests a high degree of confidence in the results.

The results further demonstrate that the methodology developed and employed during this project are feasible for understanding the timing of vein emplacement in Paleozoic sedimentary rocks. Additional analyses on sedimentary rock samples are planned for 2013 in order to further test these conclusions, and a technical report highlighting the results of the first year of this project is expected in 2013. In addition, an effort will be made to find suitable test samples of crystalline rock-hosted vein calcite in order to determine if reliable vein emplacement ages can be extracted from host rocks of igneous and metamorphic character.

4.2 GEOCHEMICAL SYNTHESIS

4.2.1 Matrix Porewater Extraction and Geochemical Analysis

In 2012, the NWMO continued to explore the development of methods to enhance porewater extraction from low permeability rock formations. Porewater is defined as groundwater within the connected pore space between mineral grains in low-permeability rock, which does not flow readily into, and cannot be sampled from, surface-drilled boreholes. On-going laboratory work includes refinement of the vacuum-distillation technique (micro vacuum-distillation, University of Ottawa), further development of the filter paper technique (University of New Brunswick), testing of an adapted squeezing technique on shale-rich rock cores from the Bruce nuclear site (University of Bern, in collaboration with CRIEPI Laboratory), and application of both out-diffusion and diffusive exchange to crystalline rock cores collected as part of the Greenland Analogue Project (GAP; discussed further in Section 4.4.4).

The research programs discussed below aim to develop and refine isotopic and geochemical analysis techniques that can be used in site investigation activities. Chemical and isotopic compositions of groundwater and matrix porewater provide information on the origin and evolution of the groundwater flow system and can be used to improve understanding of groundwater fate over geologic timeframes. In addition, near-field performance, safety assessment and groundwater transport/evolution models require knowledge of groundwater and porewater geochemical compositions.

4.2.1.1 Micro Vacuum-distillation & Crush and Leach

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 2012 work program was focused on the refinement of the techniques, in particular, the development of the micro vacuum-distillation (mVD) method (Figure 4.2). The mVD is a closed-system crushing and extraction procedure, minimizing any potential evaporative losses, and has demonstrated some advantages over the previous vacuum-distillation method, including: reduced extraction times; more efficient temperature control; smaller sample sizes, enabling precision sampling; and, rapid sampling by cavity ring-down spectroscopy. The smaller grain size samples are also subjected to crush and leach to evaluate if any differences are noted in the porewater chemistry that could be attributed to either grain size variations or the release of clay-bound waters. The mVD method has been evaluated thus far by comparing the results obtained to those determined for Porewater extracted using the vacuum-distillation technique. Further work is planned to evaluate and compare the results of the mVD technique with those from international characterization programs (e.g., Opalinus Clay, Switzerland) as a first attempt to benchmark the method against high-confidence, high-reliability data obtained using traditional methods developed for sedimentary rock of higher permeability.

Figure 4.2: Micro Vacuum-distillation - Recovery of Porewater from Low-porosity Rock for Analysis of Stable Isotopes

4.2.1.2 Filter Paper

The filter paper technique is being developed in collaboration with the University of New Brunswick. This method uses capillary action to extract porewater into a sheet of low chemical background cellulosic paper that is sandwiched between two pieces of rock core and left to absorb porewater for an extended period of time (i.e., from weeks to months; see Figure 4.3). Work to-date has shown that cellulosic sheets are capable of extracting porewater and solutes from low permeability rock formations, and that the mass of solutes extracted could be quantified by X-ray fluorescence (XRF). The technique requires very small volumes of porewater (less than 50 microlitres) to provide enough solute mass for accurate XRF analysis, which may provide a means of quantifying the in-situ composition of the major and minor solutes (Na, K, Ca, Mg, Sr, Cl and Br) in high salinity porewaters 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.

Further development of the filter paper technique in 2012 focused on the requirement for accurate measurements of both solute mass and mass of water absorbed in the cellulosic paper in order to determine accurate porewater solute concentrations. By comparing methods for solute quantification (Neutron Activation Analysis and Inductively Coupled Plasma Mass Spectrometry), the ICP-MS method was determined to be most effective at quantifying almost all of the solutes in a test water of known composition. Further work is now being done to calibrate a Near Infrared (NIR) spectrometer to allow for the determination of water mass absorbed by the cellulosic paper.

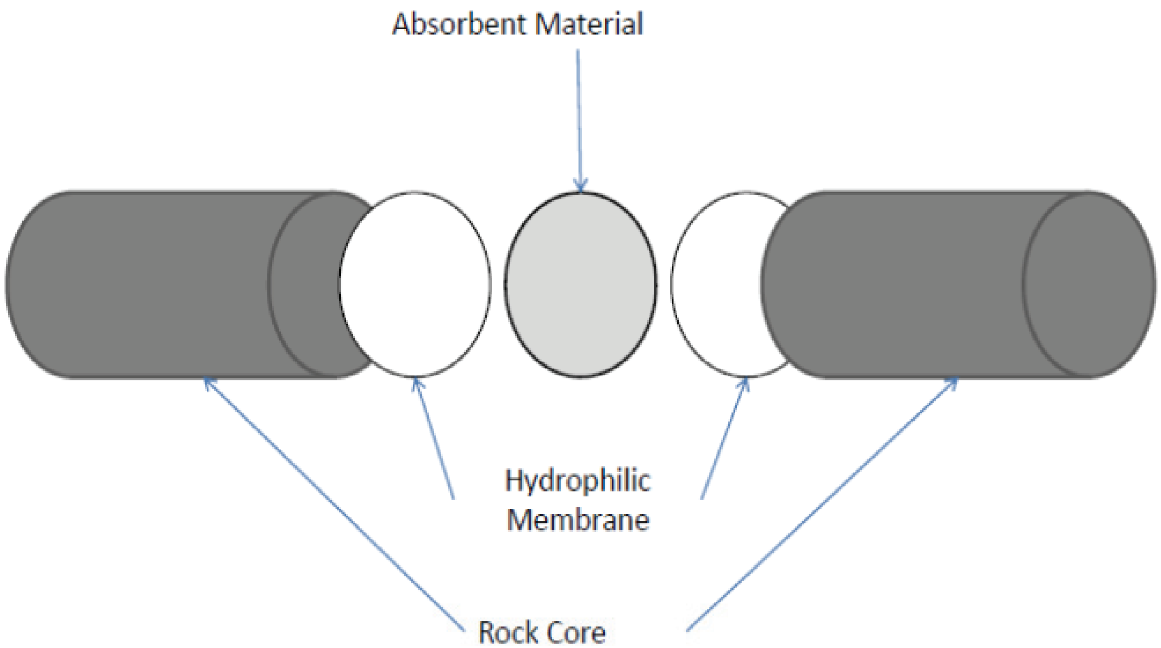

Figure 4.3: Absorbent Material Method for Porewater Extraction

4.2.1.3 Out-diffusion and Isotope Diffusive Exchange

The main objective of this work program was to document the protocols for both the out-diffusion and the diffusive exchange methods, both of which have been used in site characterization programs by POSIVA and SKB (e.g., Eichinger et al. 2010; Waber et al 2009), in the context of extracting porewaters from low-permeability crystalline rock using cores from the Greenland Analogue Project (GAP).

The out-diffusion method is based on the concept that the dissolved components within the matrix porewater in a sample can diffuse into an enclosed water reservoir and reach steady-state conditions (i.e., a state of equilibrium between the water and the host rock), and the method has been demonstrated useful in extracting matrix porewater from low porosity (0.003), low-permeability ($<10^{-17}$ m^2) rocks. A naturally saturated, intact core is immersed in deionised water for equilibration, and equilibration is determined from measurements of chloride concentration at periodic intervals. Periodic sampling results are used to establish a tracer time series and the derivation of transport properties (i.e., diffusion coefficients).

The isotope diffusive exchange technique is used to determine the stable water isotope signatures of porewater. Saturated rock pieces are equilibrated with a test water of known isotopic composition over the vapour phase, and the porewater $\delta^{18}O$ and $\delta^{2}H$ values are derived by mass balance calculations.

The work program documented this particular suite of techniques (out-diffusion and diffusive exchange) that could potentially be applied together to characterize porewaters in low permeability crystalline rock. The work program for 2012 included: 1) visualization of pore space within the crystalline rock cores; 2) out-diffusion using GAP cores to determine test water and porewater concentrations and diffusion coefficients for Cl^-; and, 3) isotope diffusive exchange to establish experimental protocols and procedures for the determination of stable water isotopic ($\delta^{18}O$ and $\delta^{2}H$) compositions in matrix porewaters extracted from crystalline rock. The final report documenting the experimental procedures and protocols is expected in 2013.

Data compilation and reporting was finalized in 2012 with respect to the adaptation of the isotope diffusive exchange technique to high salinity porewaters, and, more generally, to samples with low water activities - which are often found in deep groundwater systems in Canada. The work program, which was completed in 2011, involved: 1) the determination of factors that could potentially influence the results of the isotope diffusive exchange technique for saline solutions (using solution-solution experiments), and 2) benchmarking of the adapted diffusive exchange method using rock samples previously equilibrated with synthetic solutions of known composition (chemical and isotopic). Two rock formations were used to benchmark the improvements of the method, including the Queenston Formation shale (Ontario, Canada) and the Opalinus Clay (Mont Terri Underground Research Laboratory, Switzerland). The results of the work using the Queenston Shale and Opalinus Clay rock indicate that the diffusive exchange technique yields reliable results of isotopic composition ($\delta^{18}O$ and $\delta^{2}H$) of porewaters at all salinities measured, and highlights that the benchmarking is successful when the chemistries of both the porewater and the test water are similar. With respect to the determination of water content, it was observed that the method provided good results at high salinity (≥2.5 molal), but overestimated the values at low salinity (0.3 molal). The final report documenting the adaptation of the diffusive exchange method will be published in 2013.

4.2.1.4 Squeezing

Evaluation and application of a high pressure squeezing technique for porewater extraction has been performed in collaboration with the University of Bern. Recently, the CRIEPI Laboratory in Japan has had success extracting porewaters from low-permeability sedimentary clay and limestone formations from Switzerland using an enhanced squeezing technique (see Figure 4.4). The squeezing rig at CRIEPI is able to extract water from rock samples at pressures of up to 500 MPa, which is the highest pressure applied worldwide using comparable methods.

Considering the low permeabilities of sedimentary formations that would be suggested to host a DGR, testing of this innovative squeezing technique was undertaken as part of the Geoscience Research & Development program using three low-permeability core samples collected from the Salina F Unit, the Georgian Bay Formation and the Blue Mountain Formation shale during site characterization activities at the Bruce nuclear site. The squeezing technique was capable of extracting porewater from the Blue Mountain Formation samples only, at the maximum pressure of 500 MPa, while no water was obtained from either the Salina F Unit or the Georgian Bay Formation shale samples. The volume of water extracted from the Blue Mountain sample was less than 1 mL. The fluid has undergone geochemical analysis (Ion Chromatography) and porewater content determinations at the University of Bern, and a method to perform isotopic analysis for $\delta^{18}O$ and $\delta^{2}H$ was evaluated and tested prior to its application using the porewater sample. The final report, documenting the challenges and successes, as well as the experimental protocols and procedures, for the squeezing technique is expected in 2013.

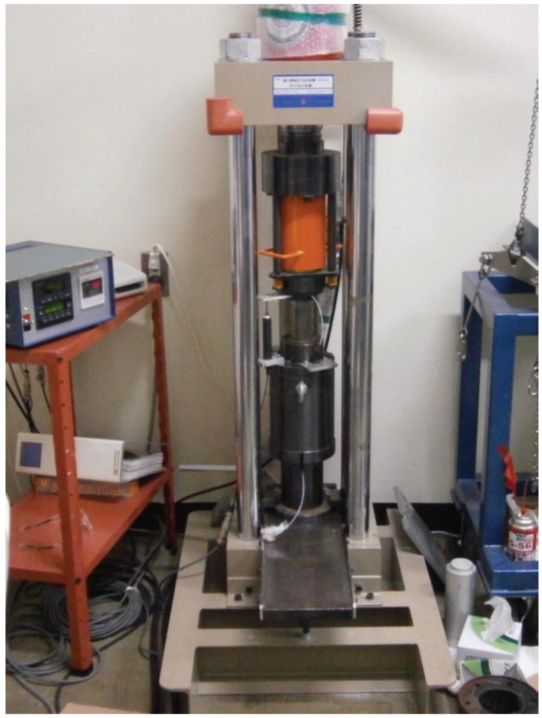

Figure 4.4: Squeezing Apparatus at CRIEPI Laboratory

4.2.2 Review of Porewater Extraction Methods

As an assessment of the Geoscience Applied Research Program's readiness to perform geochemical site characterization activities in support of APM, a review of the current porewater extraction methods adapted for use in sedimentary rock was initiated late in 2012 in partnership with the University of Western Ontario. The work program is designed to allow for the critical evaluation of two primary methodologies (i.e., micro vacuum-distillation – including crush and leach; and diffusive exchange as applied to sedimentary rocks containing highly saline porewaters) that are currently being developed and/or refined for use in APM. This peer review will provide NWMO with feedback on the effectiveness and reliability of the current experimental methodologies (strengths, weaknesses and limitations), as well as recommendations for improvement of the current methods, if any deficiencies are identified.

4.2.3 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 iodide tracer as a conservative tracer (Cavé et al., 2009a, 2009b). The X-ray radiography technique was then 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 low-permeability rock samples.

The X-ray radiography method was further developed in 2012. An improved calibration method for radiography measurements was developed 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 in Switzerland (http://www.mont-terri.ch) with both conservative (iodide) and non-conservative (cesium) tracers. The diffusion coefficients for iodide measured using the X-ray radiography technique, under confining pressures, are consistent with the published laboratory values. The diffusion coefficients for cesium estimated using X-ray radiography are within the range of published values measured in both laboratory and in-situ field-scale diffusion experiments (Figure 4.5).

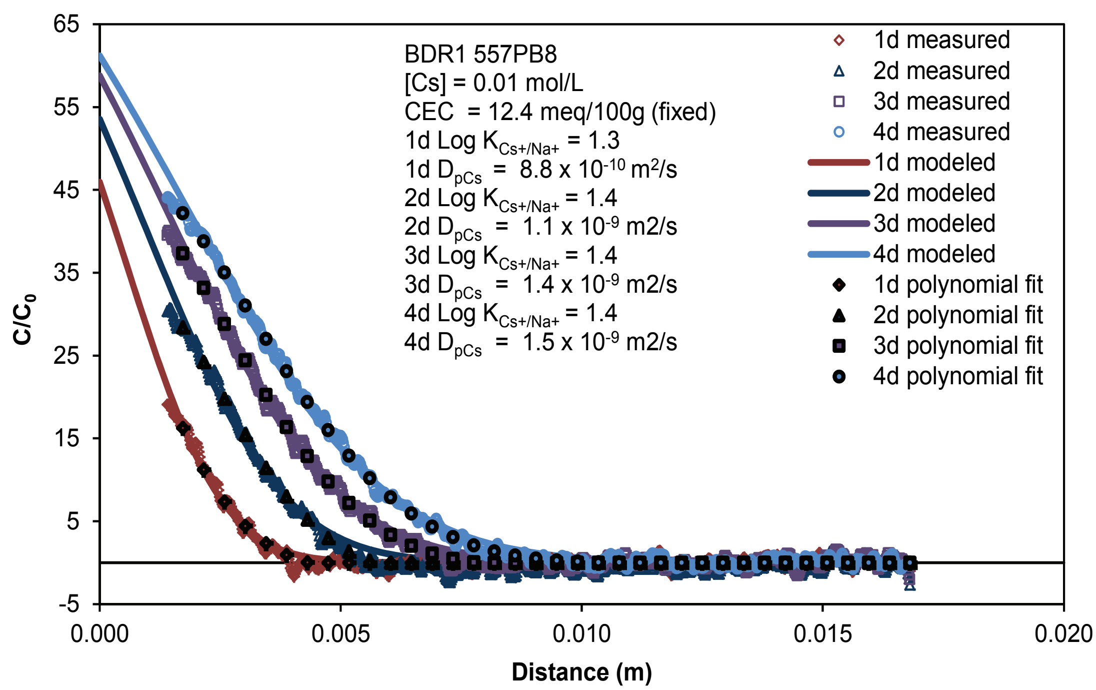

Figure 4.5: Relative Cs^+ Concentration Profiles Measured by Radiography Method and Simulated by Diffusion-reaction Using the Reactive Code MIN3P; Opalinus Clay

Investigation of the impact of partial saturation on diffusive transport in low-permeability sedimentary rocks was initiated in 2012 using the X-ray radiography method and a summary report highlighting the progress to-date is expected in 2013. Through-diffusion measurements were performed at the University of New Brunswick on Queenston and Georgian Bay formation shale and Cobourg Formation limestone (labelled in Figure 4.6 as limestone and argillaceous limestone) rocks using HTO and iodide tracers, under confining pressures (up to 12-17 MPa).

The diffusion coefficients determined under the confining pressure are 20 to 40% lower than the diffusion coefficients determined at ambient laboratory pressure (Figure 4.6). A technical report documenting these results will be published in 2013.

The development of radiography techniques will be continued in 2013 by the use of an Am-241 gamma source. The γ-ray radiography technique will be developed to: 1) assess the diffusion transport processes of both sedimentary and crystalline low permeability rocks, and 2) improve the measurement of the diffusion coefficients for partially-saturated rock samples.

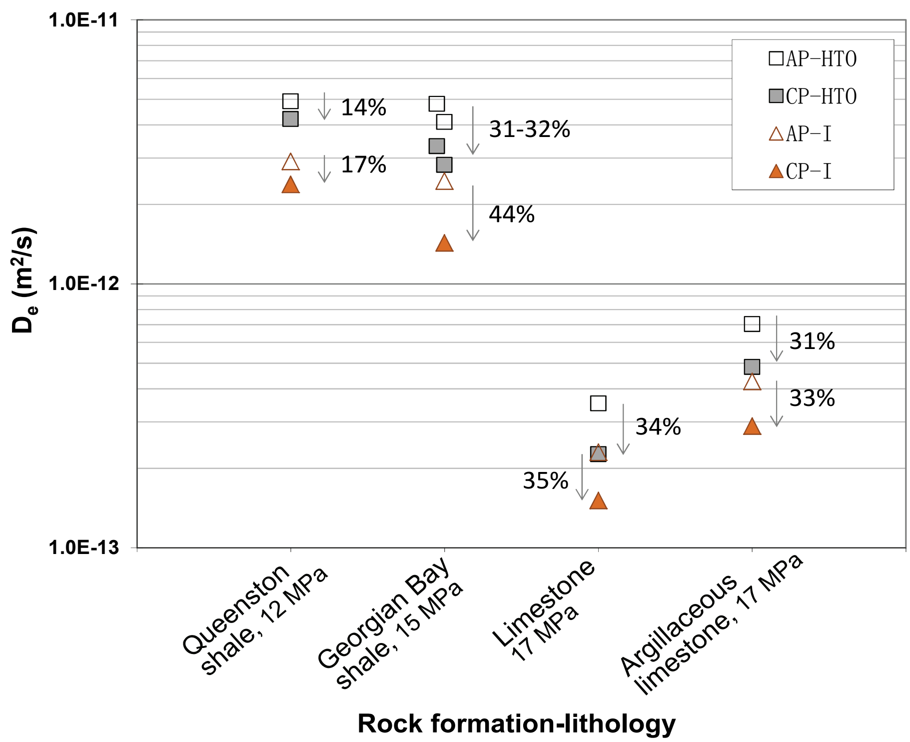

Figure 4.6: Measured Diffusion Coefficients (D_e) for Tritiated-water (HTO) and Iodide (I) Tracers: Open Symbols Represent Measurements Conducted at Ambient Laboratory Pressure (AP) and Closed Symbols at the Confining Pressures (CP) Defined in the Axis Labels

4.2.4 pH Measurements in Brines

The pH of groundwater/porewater is an important hydrogeochemical parameter for calculating the speciation and solubilities of radionuclides in support of the safety case for a deep geological repository. However, measurements of pH in highly saline groundwaters are known to be inaccurate when pH values are measured with liquid junction pH probes calibrated with standard buffers, due to changes in the liquid junction potential between standard, low ionic strength buffers and high ionic strength solutions.

In 2012, NWMO initiated a research program with the University of New Brunswick to develop an improved approach for determining the pH values of highly saline groundwaters.

Spectroscopic techniques using pH indicator dyes are currently being investigated. A calibration-free solid-state pH electrode will also be investigated in 2013.

4.2.5 Sorption

Sorption is a potential mechanism for retarding radionuclide transport from a DGR to the environment. The identification of gaps in sorption data for saline solutions was achieved in a state-of-the-science review by Vilks (2009). In 2010, NWMO initiated the development of a Canadian sorption database for highly saline groundwaters by conducting a review of the open literature and international sorption databases to find any available data relevant to Canadian sedimentary rocks (shale and limestone) and bentonite in a setting that includes Na-Ca-Cl brine solutions at near neutral pH (Vilks, 2011). This database is being augmented with sorption data measured experimentally for Canadian sedimentary rocks (and bentonite) in saline solutions (Vilks et al., 2011), as well as any new literature data.

In 2011, a two-year research program was initiated in collaboration with Atomic Energy of Canada Limited (AECL) to measure sorption values for Cu(II), Ni(II), Pb(II), U(VI) and Zr(IV) onto Canadian sedimentary rocks (and bentonite) in a highly saline Na-Ca-Cl solution with TDS of 275 g/L under aerobic conditions. Sorption tests were continued in 2012, including: 1) batch sorption tests using multiple elements Li(I), Ni(II), Cu(II), Pb(II) and U(VI) and single elements U(VI) and Zr(IV); and 2) long-term dynamic mass transport sorption tests using multiple elements Li(I) (conservative tracer), Ni(II), Cu(II), Pb(II) and U(VI) in shale by the through-diffusion method, and by the advective transport method using the High Pressure Radionuclide Migration (HPRM) apparatus (Vandergraaf et al., 1986; Vilks and Miller, 2007). The sorption coefficients measured by mass transport tests are comparable to those determined by batch sorption tests. Work in 2013 will include similar testing under reducing conditions.

In addition to measuring the sorption coefficients, batch sorption tests investigated the following aspects: 1) effect of pH on sorption; 2) sorption kinetics; 3) desorption; and 4) impact of microbes present in the laboratory on sorption.

Sorption modelling was performed using a surface complexation and cation exchange model to simulate the sorption of Ni(II), Cu(II), Pb(II) and Zr(II) onto montmorillonite and illite. The simulated sorption values for Ni(II), Cu(II), Pb(II) and Zr(II) on montmorillonite and illite are in close agreement with measured sorption values on bentonite and shale (assuming 60% illite content).

Two technical reports are expected in 2013. One will document the experimental results and the other will provide updated interim sorption values for shale, limestone and bentonite for elements/radionuclides of interest under saline conditions (based on experimental values, literature review and sorption modelling).

4.3 FLOW SYSTEM EVOLUTION

4.3.1 Reactive Transport Modelling

Reactive transport modelling is one approach for assessing long-term geochemical stability in geological formations. For example, reactive transport modelling can demonstrate: 1) the degree to which dissolved oxygen may be attenuated in the recharge region of the proposed host rock; 2) how rock-water interaction (e.g., dissolution-precipitation, oxidation-reduction, aqueous complexation, and 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 porewaters of low-permeability geological formations.

MIN3P is a multi-component reactive transport code that has been previously used to evaluate redox stability in crystalline rocks of the Canadian Shield (Spiessl et al., 2009). Over the past three years, research has been conducted in collaboration with the University of British Columbia and the University of the New Brunswick to develop an enhanced version of MIN3P (named MIN3P-NWMO) to simulate groundwater and reactive mass transport in a sedimentary basin subjected to a glaciation/deglaciation. 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 enhanced MIN3P-NWMO code was used to simulate reactive transport in a hypothetical two-dimensional sedimentary basin subjected to a simplified glaciation scenario, consisting of a single cycle of ice sheet advance and retreat (Bea et al., 2011).

In 2012, a new two-year research program was initiated to further develop MIN3P-NWMO. The focus of this work is to enhance modelling capabilities for simulation of diffusion-controlled migration in low-permeability media. The code enhancement will include: 1) implementation of the Nernst-Planck equation, which will allow the simulation of electrochemical migration in multi-component electrolyte solutions, in lieu of Fickian diffusion; 2) implementation of electrostatic effects on surface complexation and anion exclusion; and 3) inclusion of ion migration on charged mineral surfaces, providing a more comprehensive model formulation suitable for application in argillaceous formations and engineered barrier materials. The revised code will be benchmarked and verified against other reactive transport models, such as PHREEQC and CrunchFlow.

MIN3P-NWMO was used to simulate the previously published tracer diffusion and in-situ disturbance experiments at the Mont Terri Underground Rock Laboratory (Wersin et al., 2008), and to reproduce the 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). MIN3P-NWMO is currently being used to simulate the in-situ DR-A diffusion experiments with in-situ, field-scale data collected from the Mont Terri Underground Rock Laboratory (http://www.mont-terri.ch). Preliminary results were presented at the 2012 annual Mont Terri DR-A meeting and the results compared well with other reactive transport codes (including CrunchFlow and PHREEQCI). The need for additional model development for multi-site ion exchange was identified, which will be addressed in 2013. Reactive transport simulations with MIN3P-NWMO will be continued in 2013 to simulate the high salinity, oxidizing and high-pH perturbation for the in-situ DR-A diffusion experiments.

NWMO became involved in the Äspö Task Force on Engineered Barriers - Chemistry (EBS TF-C) working program in 2012. In collaboration with both the University of British Columbia and the University of New Brunswick, reactive transport simulations of the mineralogical/chemical processes occurring in the engineered barriers (compacted bentonite) will be performed. The EBS TF-C working program conducted four benchmark experiments. MIN3P-NWMO will be used to simulate these benchmark experiments and compare the simulated results with the experimental data sets and other reactive transport codes (e.g., CrunchFlow and PHREEQCI).

The development of a parallel processor version of MIN3P-NWMO (MIN3P-NWMO-P) continued in 2012. MIN3P-NWMO-P will be able to perform reactive transport simulations more efficiently. It will be able to utilize multiple processors simultaneously and will accommodate a higher degree of complexity and a finer discretization.

4.3.2 Fluid Inclusions Studies

A key issue in the long-term safety assessment of a DGR is the need to demonstrate an understanding of the evolution and stability of the groundwater flow system during the period of time for which repository performance must be evaluated. One way to understand how future events are likely to affect the future evolution of the system is to use paleohydrogeological studies to examine how the groundwater flow system has evolved in the past and to determine what factors influenced its evolution. Mineral-filled openings (veins and vugs) provide evidence that fluid migration events have occurred at some point in the geologic past. Fluid inclusions trapped within the in-filling minerals during their growth can provide reliable samples of chemical composition, density and temperature of the migrating paleofluid(s).

As part of a broader study of fracture characterization and paleohydrogeological evolution, a fluid inclusion analysis of fracture infilling material (primarily calcite) was initiated with the University of Bern. The study began with a relatively limited scope that involved petrographic examination of the vein and vug in-filling mineral phase(s) from selected intervals within Bruce nuclear site cores. This preliminary activity was followed by analysis of fluid inclusions contained within the documented calcite phases.

Four generations of fluid inclusions were distinguished during the petrographic analysis, although not all four generations are recognized in all samples. Microthermometric estimates show a general increasing and then decreasing temperature trend, from ca. 42 – 60°C during the first generation, peaking at ca. 89°C during the second generation, and cooling to < 70°C and then to between 50 – 60°C during the third and fourth generations, respectively. In terms of relative timing, these preliminary results appear to be consistent with the burial history curve and peak burial temperature estimates for the Bruce nuclear site (NWMO, 2011). Integration of the results from the fluid inclusion analysis with other datasets, primarily the radiometric age analysis of the vein calcite discussed in Section 4.1.4, provides a basis for the interpretation of the paleohydrogeological history of the ancient sedimentary environment beneath the Bruce nuclear site.

4.3.3 Evolution of Deep Groundwater Systems

NWMO continues to develop numerical methods to assess and quantify the robustness of site characterization data and predict groundwater flow and transport over geologic timescales. Numerical methods are used to assemble and test descriptive geosphere conceptual models, which are usually developed from the integration of multidisciplinary data sets that can include site-specific data. In addition, numerical models are used to refine the understanding of groundwater system evolution in both crystalline Canadian Shield and sedimentary basin environments.

In order to investigate the evolution of groundwater systems and assess the long-term performance of a DGR, NWMO is actively collaborating with researchers at the University of

Waterloo. The objective of the work is to refine numerical geoscience tools and methods to characterize groundwater systems. FRAC3DVS-OPG, the groundwater model chosen by the NWMO, is being applied to investigate the factors influencing the groundwater system evolution in regional and sub-regional settings and to test descriptive conceptual geosphere models. FRAC3DVS-OPG is a code that provides a solution of three-dimensional, density-dependent groundwater flow and solute transport in porous, discretely-fractured media.

Previous work programs (Sykes et al., 2003, 2004 and Normani et al., 2007) have provided insight into the influence of geosphere properties on deep groundwater evolution. Geosphere parameters and properties, such as salinity, fracture distribution (networks) and fracture zone properties (e.g., width and porosity) were investigated. The studies provided a better understanding of the impact of glaciation on deep groundwater systems and geosphere stability as well, and demonstrated the suitability of Mean Life Expectancy (MLE) as a performance measure when evaluating geosphere responses and parameter uncertainty.

In 2012, sub-regional scale groundwater modelling in discretely fractured crystalline rock was undertaken in support of the Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock (NWMO, 2012a). A suite of temperate and paleohydrogeologic sensitivity cases were simulated in order to illustrate the role the geosphere plays in maintaining groundwater system stability at repository depth(s). The suite of sensitivity cases investigated the role of salinity, the impact of hydraulic conductivity distributions, and hydromechanical coupling during paleohydrogeologic simulations. MLEs, depth of penetration of recharge during paleoclimate scenarios, and Peclet numbers were used as performance measures to illustrate the processes governing mass transport. For the assumed reference case, the shallow groundwater system is advective, but at greater depths, the low-permeability rock mass and decreased interconnectivity of the fracture network decreases mass transport rates. Further groundwater system stability occurs as a result of salinity gradients within the intermediate and deep groundwater systems. Paleohydrogeologic simulations were used to illustrate the long-term evolution and stability of the geosphere and groundwater systems to external perturbations. For the paleohydrogeologic sensitivity cases performed, the glacial perturbations did not materially change mass transport rates at repository depth.

Researchers from the University of Waterloo and the United States Geological Survey (USGS), as well as contributors from the University of Ottawa and the University of New Brunswick, participated in a working group on environmental tracers and anomalous pressure distributions. The pressures are measured with respect to a hydrostatic column of water at a particular location. The purpose of the working group was to examine natural tracer distributions in the context of fluid and solute transport, as well as the performance of illustrative modelling to investigate various mechanisms that could be responsible for generating both over-pressured and under-pressured conditions in low-permeability sedimentary rocks (specifically at the Bruce nuclear site; refer to Sykes et al. 2011). The mechanisms investigated include glaciation, exhumation and crustal flexure. The simulations performed by the various research groups used data from the Bruce nuclear site as a basis for establishing the properties (permeability, thickness, natural tracer and pressure distributions, etc.) of the sedimentary system. All results attest to the confining character of the Ordovician formations and support the conclusion that solute transport within the Ordovician formations is diffusive. In all simulations, the system was observed to be stable and able to adapt to external perturbations with no significant changes to physical and solute transport properties.

4.4 LONG-TERM GEOSPHERE STABILITY

A key part of the NWMO's postclosure studies is the predictability and long-term performance of the geosphere surrounding the used fuel repository. This includes developing an understanding of the potential effects of earthquakes on the repository and the influence of future glacial cycles on deep groundwater systems. The NWMO successfully concluded its involvement in the Greenland Analogue Project (GAP) in 2012 and continued to expand in the area of seismicity with two studies investigating different aspects of neotectonics (see Section 4.2.2).

4.4.1 Seismic Monitoring of the Canadian Shield

NWMO continues to gain knowledge on the seismic characteristics of low seismicity regions of the Canadian Shield in collaboration with the Canadian Hazardous Information Service (CHIS) of the National Research Council (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 2011 seismic monitoring program (Figure 4.7) were published in 2012 (Hayek et al 2012) and data from the 2012 monitoring program will be available in a technical report to be published in 2013. The events (79), recorded in 2011 are comparable with recorded events in 2010 (118 events), 2009 (82 events), 2008 (114 events), 2007 (68 events) and 2006 (83 events).

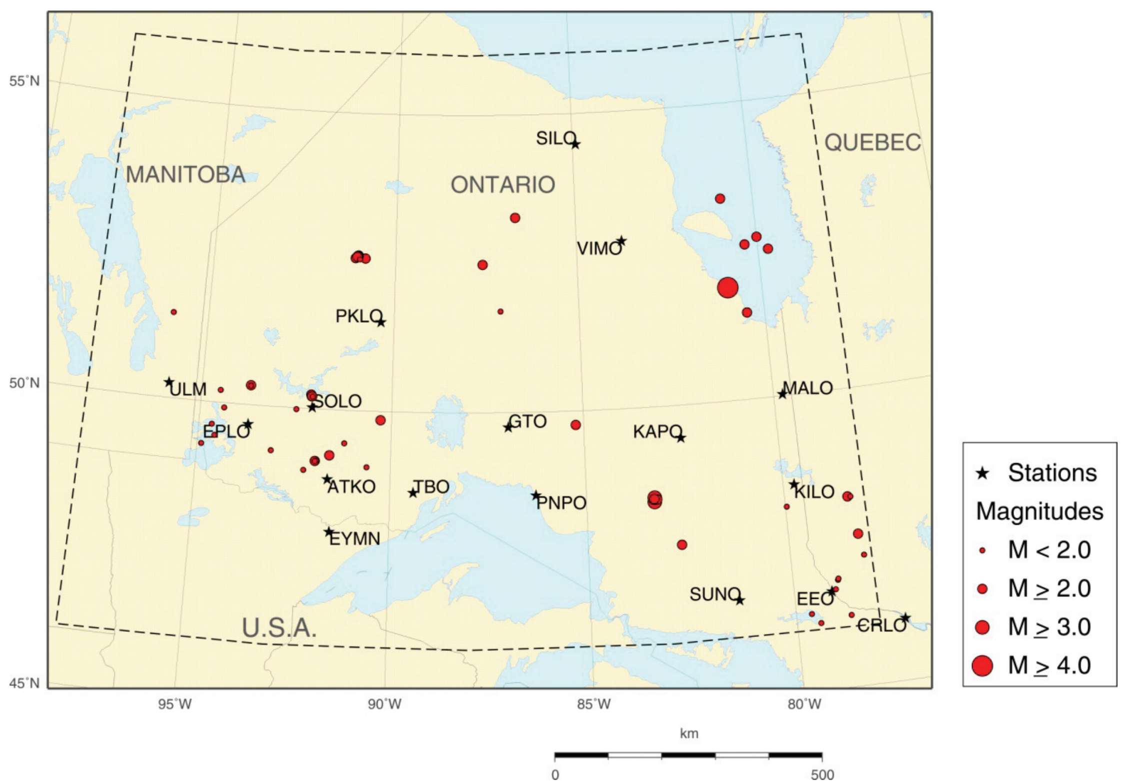

Figure 4.7: Earthquakes in Northern Ontario and Adjacent Areas, 2011

4.4.2 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 report titled Review of Paleoseismological Methods for Seismic Hazard Assessment and Their Applicability to Central and Eastern Canada was completed in 2012 by John Sims and Associates (Sims, 2012). The report describes both proven and promising paleoseismological features, as well as discussion of the various methods used to study them. The applicability of the study of these features, and the methods used, are discussed in the context of the Quaternary geological and seismological settings of both Ontario and Saskatchewan.

The NWMO also continues to develop numerical methods in partnership with the University of Calgary, exploring: 1) the role of ice sheets on potential crustal anisotropies; 2) modeling the spatio-temporal variation of stress and fault stability; and 3) the stresses induced from glacial loading, including those from bending of the lithosphere and relaxation of the mantle, which are superposed on the overburden stress, pore fluid pressure and ambient tectonic stresses to give the total stress. It was found that a thrust background stress regime is able to explain many of the observed data in Laurentia and Fennoscandia. The size of the ice sheet and its deglaciation history are found to have large effects on the onset timing of earthquakes inside and outside of the ice margin. This work is considered important for regional-scale modeling of long-term geosphere stability and for estimating how localized structures may be influenced by far-field effects. These findings were summarized in a report produced by the University of Calgary (Wu, 2012).

4.4.3 Glacial Systems Model

One essential element in assessing the potential impact of glaciation on a DGR is the ability to adequately predict the surface boundary conditions during glaciation. 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 simulations 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 method 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.

There are several aspects of the GSM that require further development to refine predictions of glaciation boundary conditions. In the present model, which is based upon the "shallow ice approximation", longitudinal stresses are neglected. Furthermore, the representation of the interaction of ice streams with the ocean into which they discharge is not clearly defined along the model boundaries. 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 and is being addressed in the current update of the GSM. The objectives of the University of Toronto work program are to maintain and improve the GSM. This will be achieved by improving the way that the flow of ice over the landscape is described, specifically by implementing of a more robust representation of the physics involved in the motion and dynamics of an ice sheet.

4.4.4 Greenland Analogue Project (GAP)

In collaboration with SKB and POSIVA, the NWMO continued its involvement in the Greenland Analogue Project (GAP) in 2012. The objective of this four-year project (2009-2012) is to advance the understanding of processes associated with glaciation (see Figure 4.8). The GAP will improve our knowledge of the potential 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.

Figure 4.8: Moulin on the Greenland Ice Sheet, at the GAP Field Site Near Kangerlussuaq, Greenland

Following an introductory field campaign in 2008 near Kangerlussuaq, Greenland, the GAP field program began in 2009 and included the 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. A deep, inclined borehole (DHGAP04, ~687 m borehole length) was drilled under the margin of the ice sheet. 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 porewater samples were collected from the deep borehole.

In 2012, the final full season of the GAP project continued from previous years, including a geochemical sampling program of surface water bodies and a pingo. Radar surveys, and the drilling of boreholes through the ice to the ice-bed interface, concluded in 2012. Planning is underway for comprehensive final reporting, detailing the results of the four-year field campaign and the associated data and modelling interpretations. Final reports (Volume 1 and 2) are projected for publication in 2014-2015.

4.5 GEOMECHANICAL ACTIVITIES

4.5.1 Assessment of Excavation Damage Zone (EDZ)

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 dimensions of the 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 2012, investigations on existing excavations in a number of underground research facilities and mines, including those at Äspö in Sweden, Mont Terri and Grimsel in Switzerland, and Bure in France, were performed to understand the characteristics of excavation induced failure in various rock types under different ground stress conditions. In addition, EDZ data was also obtained at the Niagara Tunnel Project in Niagara Falls, Ontario, and at the Gonzen mine in Switzerland. One of the most notable observations was the influence of bedding on the failure process in shales of southern Ontario.

The orientation of the bedding has a major impact on the excavation induced damage and the failure process. The propagation of spall fractures is assisted by the thinly laminated rock masses by providing (often) linear failure pathways. In carbonates, however, the bedding is often non-linear in nature. Other observations at the Gonzen mine, in the Quintner limestone, show that long-term stability of excavations is possible without support, where room and pillar areas show only minimal bedding parallel slabbing after more than 50 years of inactivity. Stress risers, such as pillars and sharp corners of the excavation periphery, show a strong influence on brittle spalling behavior. The influence of calcite veining was also observed at the excavation scale and investigated with laboratory testing of Quintner limestone (Figure 4.9) in collaboration with the Swiss Federal Institute of Technology (ETH) in Zurich. It is the intent of the work program to utilize these in-situ observations and laboratory studies to improve predictive numerical models, which, in turn, can be used to determine likely dimensions of the EDZ in comparable sedimentary environments.

Laboratory testing on the fracture growth on Lindsay limestone, and other limestones from Niagara Falls, continues at CANMET and at the Royal Military College of Canada in order to investigate the influence of strength anisotropy and bedding planes on rock response. The findings from these laboratory tests are important because the strength thresholds are necessary numerical model input. It is anticipated that all testing will be completed in 2013.

The development of a new geomechanics classification system, specifically for carbonate and argillaceous rock, was initiated in 2012 and is in progress. The application of this classification will expand to other sedimentary rock types, such as shale, 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.

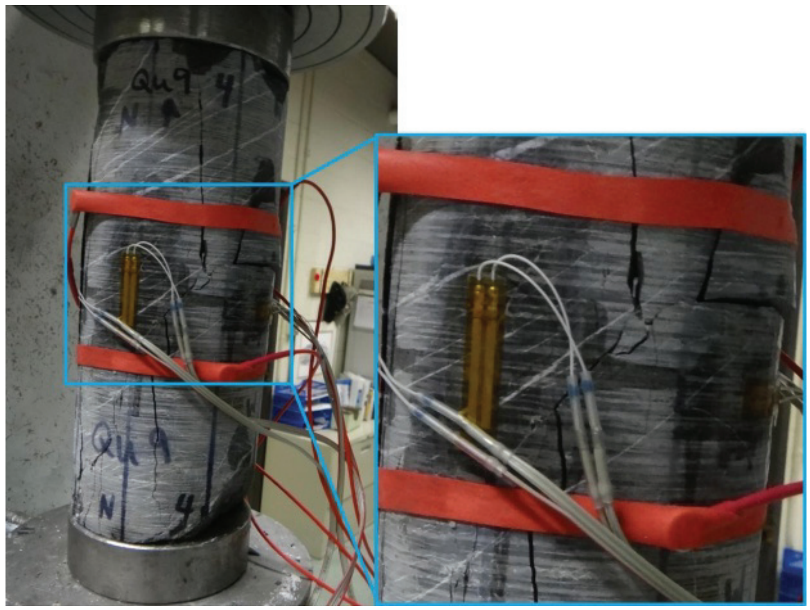

Figure 4.9: Uniaxial Compression Test of Quintner Limestone

In 2013, research will focus on the management of EDZ using excavation cut-offs. For cut-off design, it is important to understand post-yield and time-dependent deformation processes, such as dilation and creep, and how these can be best captured numerically. Such studies are already underway, including dilation modeling and assessment of rock mass creep. Dilation and creep aspects will be particularly important if cut-off structures are to be excavated many years after the repository excavation, which requires understanding of the influence of the cut-off on the rock mass behavior. The research will examine excavation intersections and cut-off shapes and how these influence the EDZ. Additional research will be conducted in 2013 and will utilize discrete element models to further refine the EDZ delineation guidelines used in continuum models – to ensure that the rock mass behavior is captured correctly in the process.

4.5.2 Advanced Measurement of THM Properties

The NWMO's geomechanical research program on thermo-hydro-mechanical (THM) processes concentrates on near-field rock mass response. A coupled THM experimental work program has been underway at the University of Toronto since 2011. The objective of this research is to characterize THM coupled processes and properties of sedimentary rock in order to assess the extent to which the properties of a host rock will be altered by heat generated by used nuclear fuel in a DGR. The THM test program consists of three groups of experiments: 1) determination of the physical properties of the rock; and 2) uniaxial compression tests on dry and re-saturated samples, tested at ambient temperature and thermally treated at 50°C, 100°C and 150°C.

In 2012, the final phase of hydro-mechanical (HM) and thermo-hydro-mechanical (THM) testing of Cobourg (Lindsay) limestone samples, retrieved from St. Mary's Cement quarry in Bowmanville, was completed. These experiments were performed using non-destructive or destructive, geophysically instrumented Hoek-type cells capable of applying hydrostatic and deviatoric stresses at various temperatures (Figure 4.10). In these experiments, it was found that samples tested under controlled HM or THM conditions exhibit the same characteristics at both room (HM) and elevated (THM) temperatures. In Figure 4.11, the evolution of seismic wave velocities with hydrostatic stresses on a typical test sample shows an initial compaction during loading stages, as well as the expansion during heating stages.

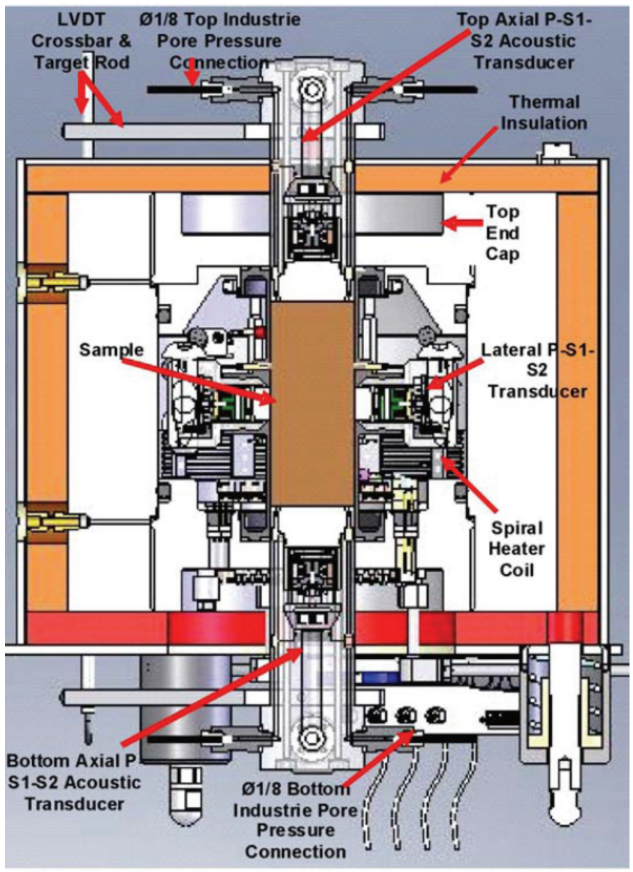

Figure 4.10: Cross-sectional View of the Geophysical Imaging Cell Used for Performing THM Experiments

Permeability values measured for heat-treated and non-heat-treated specimens show a consistent trend. The permeability at a respective target temperature shows a reduction proportional to the amount of thermal treatment experienced. The testing confirms that the initial closure of micro-cracks and compaction occurs in association with increased thermal pressurization, decreasing the permeability of the rock. The magnitude of the permeability values measured are consistent with steady-state and transient hydraulic pulse test results on limestone samples from the same quarry tested by McGill University (Section 4.5.4; Selvadurai and Jenner, 2012).

In 2012, an inter-laboratory comparison between geomechanical testing performed by McGill University, Queen's University and the University of Toronto was initiated. The purpose of this comparison is to ensure consistency in test results generated by the three laboratory facilities, and to take corrective actions if discrepancies are observed. In the first round of testing, unconfined compressive strength (UCS) was measured using samples of Indiana limestone prepared from a relatively homogenous rock block with the same orientation of core retrieval. This testing was completed and the results compiled in 2012. A detailed comparison is currently underway at the University of Toronto.

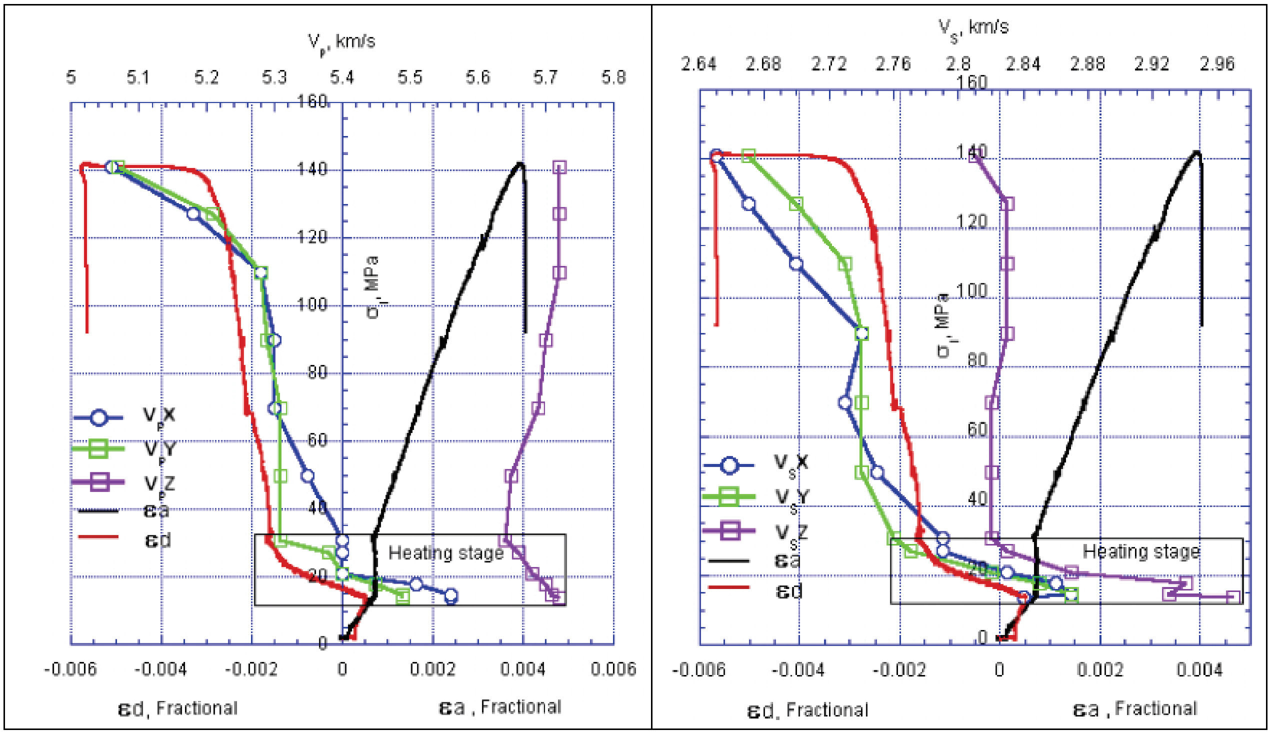

Figure 4.11: THM Test Result Showing Evolution of Axial, Diametral Strains and VP and Vs (measured along three axes) as a Function of Axial Stress for a Specimen Subjected to Heating up to 100 ºC

4.5.3 Synthetic Rock Mass Program

The Synthetic Rock Mass (SRM) technique is a new approach for predicting rock mass behavior by using discrete element logic to capture the failure of individual components of a rock mass (i.e., fracture of intact rock and/or failure along pre-existing discontinuities). The SRM approach is based on a general realization and acceptance that the behaviour of a rock mass is controlled by two main components: 1) fracture of intact rock, and 2) movement along pre-existing discontinuities in the rock mass. Conventional continuum and some discontinuum modelling methods for simulating mechanical behaviour of rock do not treat these two components as separate processes affecting the same elemental volume of rock. Instead, the components are combined using a descriptive constitutive model to simulate the damage progression through intact rock zones or failure along pre-defined failure surfaces.

The SRM research at NWMO is a multi-year research program that started in 2011. The program is conducted in collaboration with the Swedish Nuclear Fuel and Waste Management Company (SKB), Queen's University and the University of Alberta. The work program advances conventional design techniques by simulating rock mass response at a variety of critical scales, involving the application of discrete element methods in established numerical codes, such as Universal Distinct Element Code (UDEC) and Particle Flow Code (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.

For the study of excavation damage zones around underground openings through the SRM approach, the model must be capable of correctly simulating initiation, accumulation and coalescence of fractures leading to failure in different stages of rock response. A key step is the calibration and verification of simulated laboratory scale testing data, such as direct tensile, indirect tensile (Brazilian), uniaxial and triaxial compressive tests, with actual laboratory data. Figure 4.12 shows three cylindrical models corresponding to fine, medium and coarse grain size distributions in the specimens. The large assemblies of spherical elements in the model represent separate grains that are connected to each other by weak intergranular bonds. The clusters of spheres in the grained-based models are not rigid and will allow cracks to propagate through them. This modeling approach is essential to develop breakable grains (clusters).

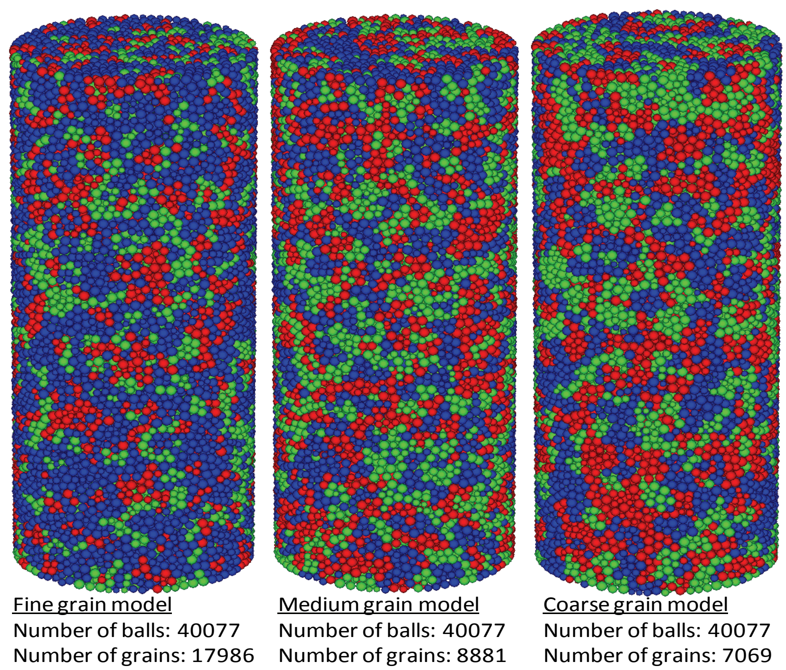

Figure 4.12: Fine, Medium and Coarse-grained SRM Models

An alternate method, using 3D Voronoi tessellation in 3DEC, was also developed to generate grain-based models. Both PFC and 3DEC grained-based models will be calibrated and verified using laboratory test results in 2013.

A study of the effect of model size on the accuracy of the generated Discrete Fracture Networks (DFNs), in terms of statistical representativeness, was initiated in 2012 and is still in progress. Work to-date has demonstrated that adequately sized bounding regions limit the total number of realizations required for consistent results. Further research will be performed to investigate the relationship between average block size and representative model limits, and the effect of fracture size and fracture intensity on average block size.

4.5.4 Study of the Mechanical and Hydraulic Properties of Limestone

On-going experimental research programs at McGill University are examining the effects of anisotropy and scaling on measured hydro-mechanical properties.

The research on both geomechnical and fluid transport characteristics of the intact Cobourg limestone, through multi-scale and anisotropic evaluation, will continue in 2013. Larger-scale specimens will be employed (from 75 mm to 300 mm in diameter) than in previous studies, both for Hoek-Cell (Figure 4.13) and plug compression tests. This is essential to establish the accuracy and reliability of geomechanical and fluid transport parameters obtained from conventional tests using smaller diameter (75mm) samples. This test program will be the first attempt in Canada on large diameter samples, and will be the first of such tests on large diameter Cobourg limestone samples. To increase the understanding of the influence of sample heterogeneities, Computed Tomography (CT) scans of selected samples will be performed prior to any geomechanical and fluid transport testing.

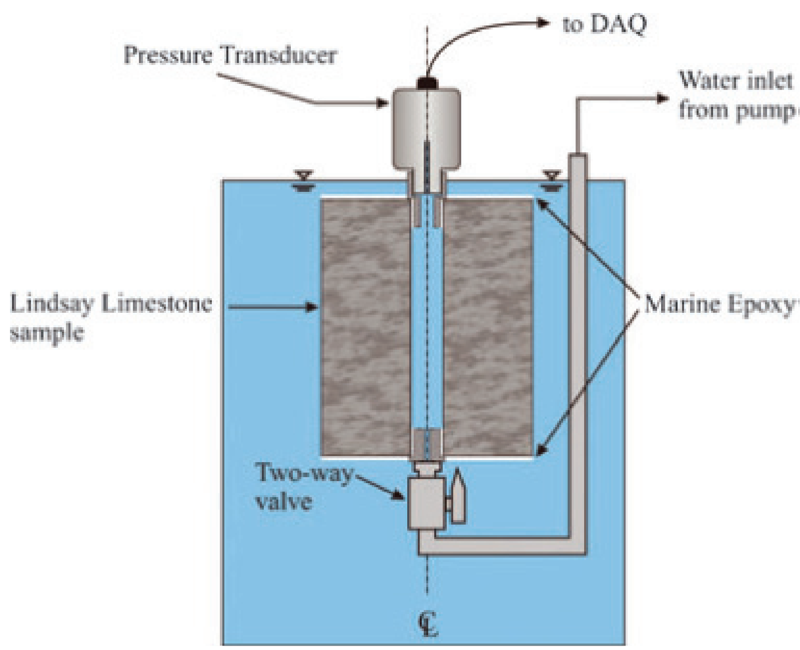

Figure 4.13: Cross-section of a Typical Hoek-Cell Test Specimen

This range of sample sizes is intended to adequately capture the role of the 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.

4.5.5 Mont Terri Project, Switzerland

Through the Geoscience Research program, NWMO continues to participate in experiments conducted in-situ at the Mont Terri Project underground research laboratory in Switzerland. Phase 18, which began in July of 2012, includes NWMO involvement in eleven different experiments, all of which contribute to the development of new technologies, field methodologies and numerical modeling approaches relevant to safety assessment, engineering and geoscience.

NWMO is actively contributing to several experiments by supporting involvement of university researchers or consultants. An example is the Diffusion, Retention and Perturbations experiment (DR-A), where the aim is to create a unique database of results for an induced disturbance during an in-situ diffusion experiment, against which the predictive capabilities of current reactive transport models can be tested (verification). Drs. Uli Mayer (University of British Columbia) and Kerry MacQuarrie (University of New Brunswick) are participating in the modelling group using MIN3P-NWMO as an opportunity to benchmark this code against other reactive transport modelling codes.

NWMO is also involved in Gas Path through Host Rock and along Seals (HG-A), an experiment examining gas pathways through a host rock and along seals. The objectives of this experiment are to: 1) assess the role of the EDZ as an important gas path; 2) evaluate sealing processes along the EDZ; and, 3) determine rock permeability at the scale of a tunnel (macro-permeability). On behalf of NWMO, Geofirma Engineering Ltd. has been involved in numerical simulations for this experiment.

The goal of the Iron Corrosion in Bentonite experiment (IC-A) is to provide confirmation of the long-term anaerobic corrosion rate of carbon steel in compacted bentonite under repository-relevant conditions. These in-situ (in borehole) corrosion tests will assist in building confidence in predictions of canister lifetimes, and will provide confirmation of the effect of the bentonite buffer on microbial activity and microbially-influenced corrosion. Prototype Canadian carbon steel materials were prepared by CANMET for NWMO and samples of these materials have been placed in modules within the borehole. The modular design allows for extraction and analysis of the carbon steel samples, and analysis for corrosion products after different lengths of time, as well as the placement of new samples and/or materials in the boreholes during the experiment.

5. REPOSITORY SAFETY

The objective of the repository safety program is to evaluate and improve the operational and long-term safety of any candidate deep geological repository. In the near-term, before a candidate site has been identified, this objective is addressed through case studies and through improving the understanding of important features and processes. Activities conducted in 2012 to further this objective are described in the following sections.

Garisto et al. (2009) provides a technical summary of information on the safety of a repository for used nuclear fuel. The report summarizes key aspects of the repository concept and explains why the repository concept is expected to be safe (see Table 5.1). The report is non-site specific and considers both Canadian Shield and sedimentary rock formations. Several design concepts are considered.

Table 5.1: Typical Physical Attributes Relevant to Long-term Safety

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

5.1 MODEL AND DATA DEVELOPMENT

5.1.1 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 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 generated from radiolysis, but much larger amounts are generated as a result of corrosion of the steel vessel of the container.

The 2012 program on UO_2 dissolution continued at the University of Western Ontario and included:

- Development of a model to predict the influence of steel corrosion products (Fe^{2+} and H_2) on the fuel corrosion rate (Wu et al., 2012); and
- Determination of the kinetics of H_2O_2 reduction and decomposition on a SIMFUEL (UO_2) surface (Razdan et al., 2012; Wu and Shoesmith, 2012).

A review of the work carried out at the University of Western Ontario to study the corrosion of UO_2 fuel inside a failed nuclear waste container, over the period January 2006 to December 2010, was also published in 2012 (He et al., 2012).

A combination of electrochemical and open circuit corrosion measurements on UO_2 electrodes and surface analytical techniques were used in the investigations. 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 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 5.1.1.1 and 5.1.1.2.

5.1.1.1 Model to Predict the Influence of Redox Conditions on Fuel Corrosion

The preliminary model of fuel corrosion, developed in 2011 using COMSOL, was improved in 2012. The aim of this model is to predict the corrosion rate of fuel inside a failed used fuel container (fuel corrosion can only occur if water contacts the fuel). In particular, the model determines the effects of steel corrosion products (Fe^{2+} and H_2) – which influence redox conditions inside a failed container – on the fuel dissolution rate (Wu et al., 2012). 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 model are:

- Radiolytic production of H_2O_2;
- H_2O_2 reduction on UO_2 and noble metal particles, with the concomitant oxidation of UO_2;
- H_2 oxidation on noble metal particles, with the concomitant reduction of U(V) or U(VI) to U(IV);
- Homogeneous reaction of H_2O_2 with Fe^{2+} (Fenton reaction), resulting in consumption of H_2O_2 and formation of Fe^{3+}; and
- H_2O_2 decomposition (the reaction of the O_2 produced by H_2O_2 decomposition with UO_2 is not currently considered in the model).

Radiolysis is assumed to occur uniformly 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 Fe^{2+} and H_2 (assumed to be formed by corrosion of the iron container). Model calculations indicate that the fuel corrosion rate is almost independent of the selected diffusion length and the assumption that radiolysis occurs uniformly within the thin layer of solution at the fuel surface.

The Fenton reaction will consume H_2O_2 and, thus, would suppress fuel corrosion. However, as shown in Figure 5.1, the influence of Fe^{2+} is relatively minor. A concentration of Fe^{2+} approaching the solubility limit for $Fe(OH)_2$ would be required before any significant influence of the Fenton reaction on fuel corrosion would be observed (Wu et al., 2012).

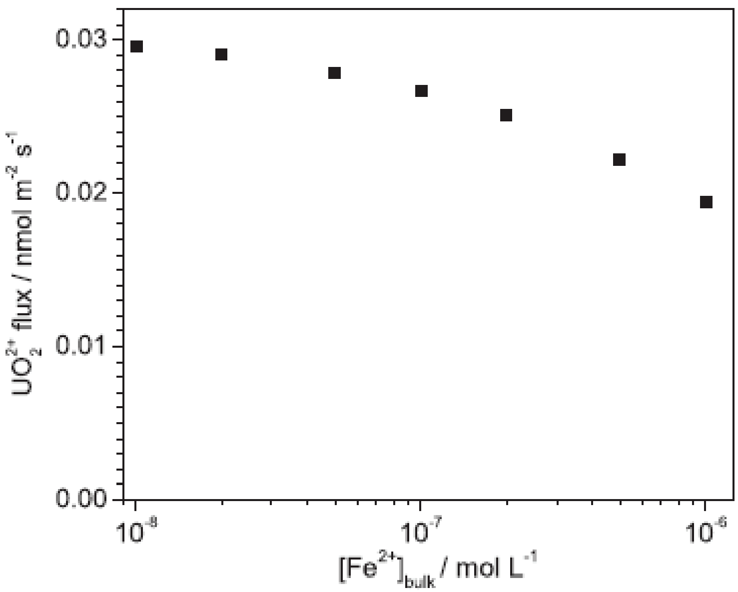

Figure 5.1: Influence of Fe^{2+} Concentration on the UO_2 Corrosion Rate, Expressed in Terms of the Flux of UO_2^{2+} Leaving the Surface

One purpose for developing the model is to examine the influence of H_2 on the fuel corrosion rate. The model shows that the fuel corrosion rate decreases linearly as the H_2 concentration increases. Extrapolation of this relationship to a zero fuel corrosion rate predicts the critical H_2 concentration (i.e., the H_2 concentration at which the net fuel dissolution rate is approximately zero).

Figure 5.2 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 (Wu et al., 2012). These results are somewhat different from those obtained with the preliminary model described in Kennell et al. (2012) because of model improvements. The critical H_2 concentration reaches a maximum of ~1.4×10^{-5} mol/L about 100 years after disposal (the time of the maximum alpha radiation dose from fuel), and decreases substantially after about 10^4 years. The maximum critical H_2 concentration corresponds to a H_2 partial pressure of about 0.017 bars, a relatively low level. These findings, which appear to be consistent with experimental results, suggest that the hydrogen generated by corrosion of the steel vessel could greatly limit the fuel corrosion rate (Shoesmith, 2008). Considerable uncertainty remains in some of the rate constants used in this model and these critical H_2 concentrations are likely to be conservative.

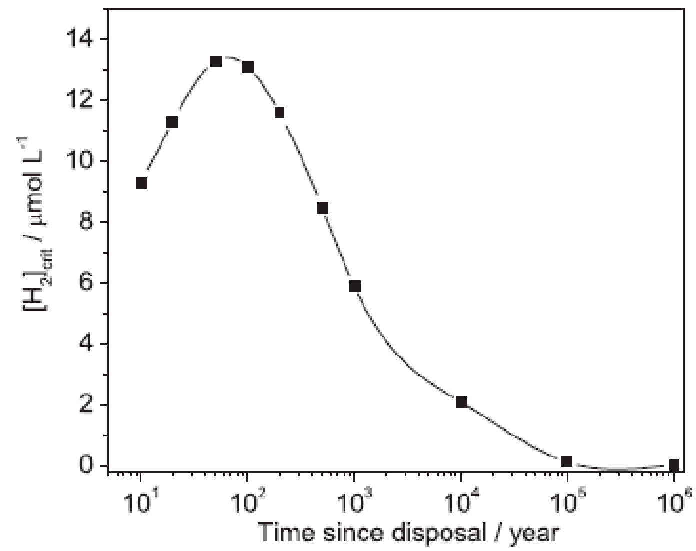

Figure 5.2: Critical H_2 Concentration as a Function of Time after Disposal for CANDU Fuel with a Burnup of 220 MWh/kgU

5.1.1.2 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 behaviour of the used fuel.

In 2012, a preliminary electrochemical study of the effect of different doping elements on H_2O_2 reactions (oxidation and reduction) on SIMFUEL surfaces was completed (Wu and Shoesmith, 2012). Cyclic voltammograms (CV) were recorded on 3at% SIMFUEL in Ar-purged 0.1 M NaCl solution. Three different SIMFUELs were used: 1) doped with noble metals (e.g., Ru and Mo), 2) doped with rare earths and other elements that dissolve in the UO_2 lattice (e.g., La, Ce, Zr and Ba), and 3) doped with both noble metals and rare earths. The CVs in H_2O_2 solution showed a significant difference between the electrode doped with noble metals and the other two electrodes. The reduction currents with the noble metal doped electrode were much lower than for the other two electrodes. The reason is thought to be the high resistance of the electrode without rare earth doping. In addition, experiments of H_2O_2 decomposition were conducted in solution containing 0.001 M H_2O_2 and 0.05 M Na_2CO_3. After the electrodes were kept at +0.2 V for 4.3 hours, the change in the number of moles of H_2O_2 and uranium in solution was determined by solution analysis, and the total anodic charge was calculated from the measured current.

Figure 5.3 shows that the decrease in the amount of H_2O_2 is apparently higher in the presence of noble metals, and is generally higher than the total anodic charge, indicating that H_2O_2 decomposition is the major cause of the decrease in H_2O_2 in the presence of noble elements. This is important because the decomposition of H_2O_2 would lead to lower fuel dissolution rates.

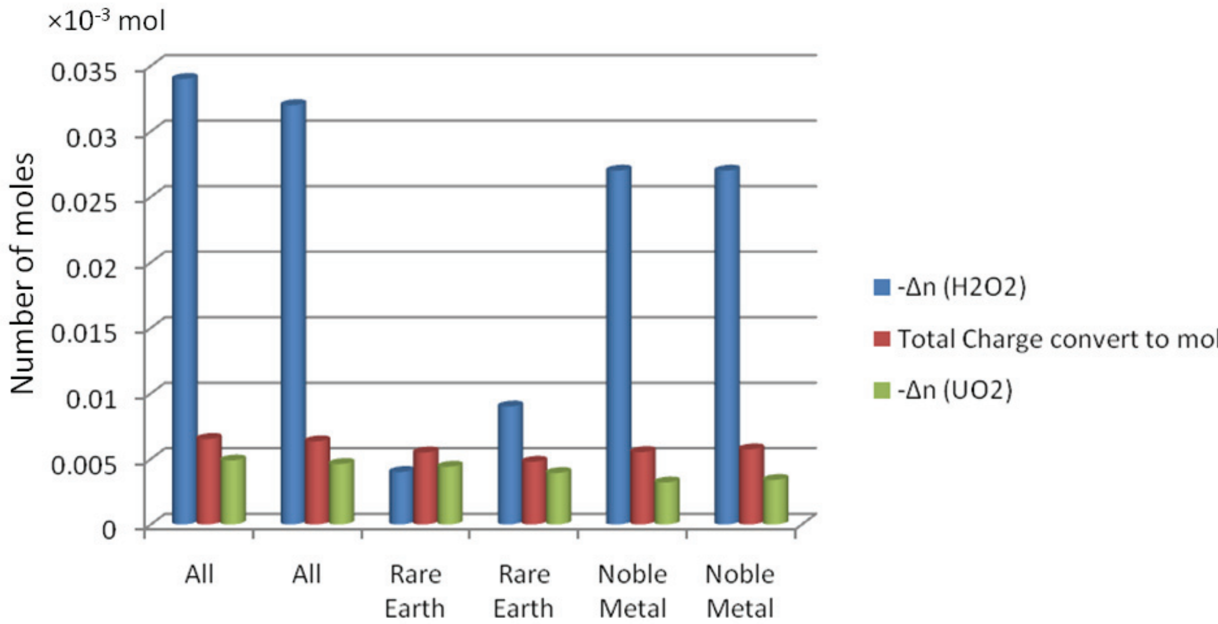

Figure 5.3: Changes in the Amount of H2O2, Total Anodic Charge and Amount of UO2 in (duplicate) Electrochemical Experiments Using Different SIMFUEL Electrodes

Earlier work (Keech et al., 2008) identified a change in the mechanism of the electrochemical reduction of H_2O_2 on SIMFUEL surfaces with pH. In 2012, the details of this change in mechanism with pH, and how it is influenced by the composition of the UO_2 surface, were identified (Razdan et al., 2012). The change in mechanism occurs at low pH values (pH <4), outside the neutral to slightly alkaline conditions (pH 6 to 9.5) expected in a repository. Thus, this work extends our understanding of the electrochemical reduction of H_2O_2 on UO_2 surfaces.

5.1.1.3 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, and 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 are only available for a few key elements (Gobien and Garisto, 2012; Garisto et al., 2012) because such measurements are complex and costly.

For radionuclide and chemical element screening, instant release fractions are required for many elements. In the case of elements for which measured fractions are not available, the values can be estimated based on the diffusion coefficients of the elements in the fuel while the fuel is in the reactor, and based on the chemistry of the elements in the fuel (Gobien and Garisto, 2012). For example, an understanding of which elements form solid solutions with UO_2, and which elements form metallic or oxide precipitates in fuel, would be important (Kleykamp, 1985). This methodology was used to conservatively and systematically estimate the instant release fractions for elements for which measured data are not available. The estimated values are listed in Gobien and Garisto (2012), along with the basis for the selected values of each element of interest. These fractions were used in the screening study considering a conceptual repository design in crystalline rock (NWMO, 2012a).

5.1.1.4 Fuel Burnups and Power Ratings

Discharge burnup and maximum power rating are key parameters for used nuclear fuel in that they largely determine the inventory of radionuclides, as well as the fraction of fission products that are able to migrate to the fuel gap and grain boundaries.

In 2006, an Ontario Power Generation (OPG) report was issued that summarizes these data for fuel discharged from the Darlington, Pickering A and B, and Bruce A and B nuclear reactors during the period from 1970 to 2006 (Wilk and Cantello, 2006). This report presents frequency histograms for burnup and maximum power rating for each station, together with tables showing the maximum, median, 90th, 95th, and 99th percentile values.

In 2012, a work program was initiated to update this information by incorporating 2006-2012 data, and by including information for the Gentilly 2 and New Brunswick Power reactors. Figure 5.4 shows summary information from this new work, the results of which will be published in a technical report in 2013.

5.1.2 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 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 3.2.2.

5.1.2.1 Failed Container Model

The used fuel container is a barrier to the release of radionuclides; it provides a barrier by preventing access of water to the used fuel. However, the containers will eventually corrode or fail, thereby allowing water 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 and slow dissolution.

For a copper container, the assumed non-corrosion failure mode is via a small weld defect that goes unnoticed during the fabrication and inspection processes. A 1/5000 defect frequency is assumed, with the failure being a small “pinhole”-like defect that extends through the copper shell.

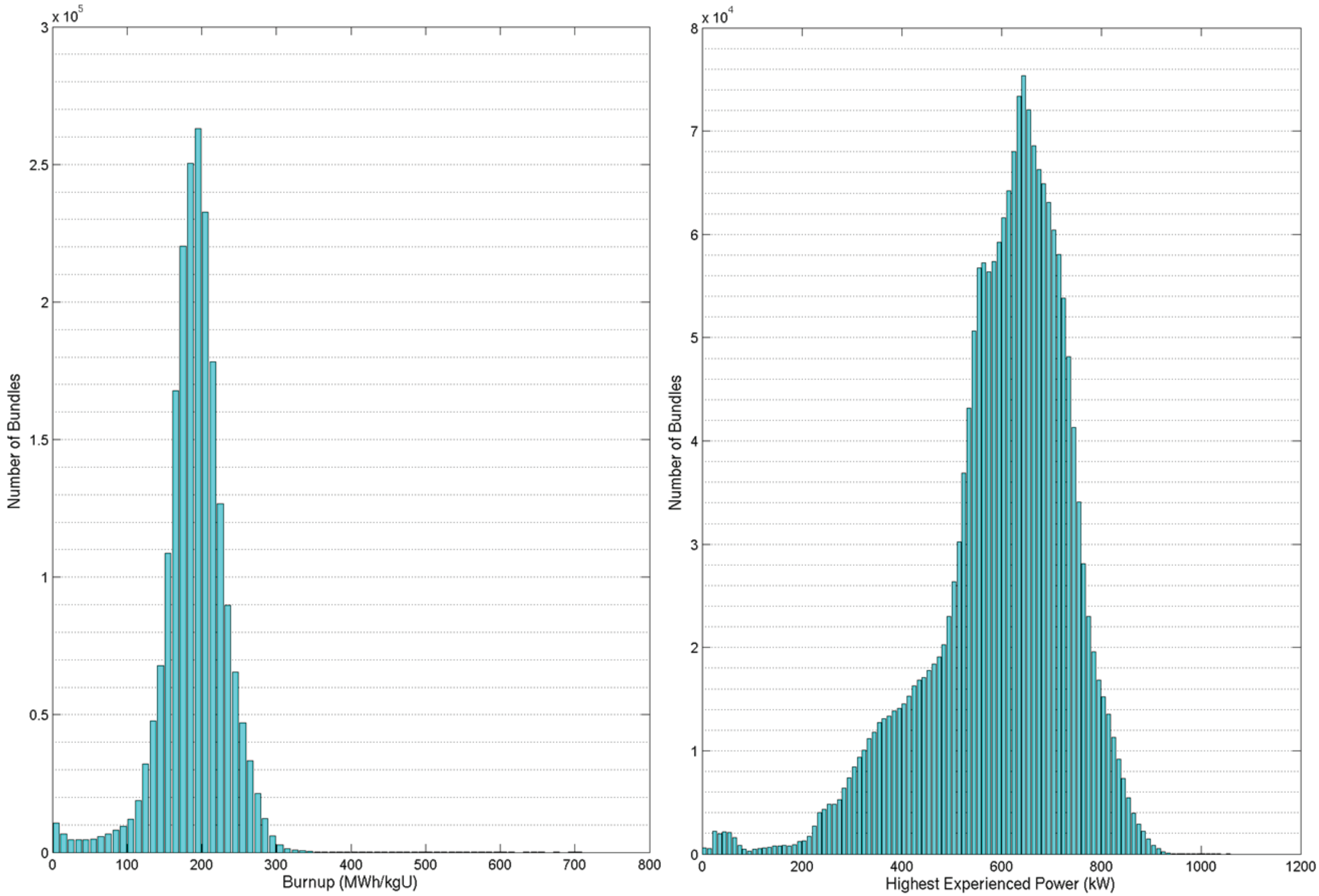

Figure 5.4: Fuel Bundle Burnups and Power Ratings for All Stations

As part of the exploration of options for sedimentary rock conditions (see Sedimentary Case Study, Section 5.2.1.2), containers made exclusively of steel are being considered also. These containers would be essentially identical to the reference 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 anticipated that the containers will experience corrosion related failures during the timeframe of interest. Such failures would not be consistent with the "pinhole" defect failure mode assumed for a copper container.

The COMSOL code has been used to model the radionuclide releases from a corroded container in a placement room. Results show that because the container is no longer an effective barrier:

- The flux of highly soluble elements is limited only by the fuel dissolution rate; and
- The flux of solubility-limited elements increases proportionally to the surface area through which radionuclides can diffuse.

This release model will be used in future case studies whenever a failure mode different from a 'pinhole' defect is required. The model will be summarized in Gobien and Garisto (2013).

5.1.2.2 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 never mobilize in large amounts (N.B. under some groundwater conditions, colloid transport may be important).

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, both the Pitzer (Specific-ion Interaction) and SIT (Specific Ion Theory) approaches are used to calculate solubilities at high salinities. While the Pitzer approach is generally considered better at very high salinities, it currently has a more limited thermodynamic dataset. 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 for 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 2012; 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. Because such calculations would benefit from the availability of a thermodynamic database appropriate for the conditions existing in

Canadian groundwaters, efforts are now focused on developing such a database (refer to Section 5.1.2.3).

5.1.2.3 Thermodynamic Database Review

NWMO continues to support the joint international Nuclear Energy Agency (NEA) effort on developing thermodynamic databases for elements of importance in safety assessment (Mompeán and Wanner, 2003). The third phase of Thermochemical Database (TDB) Project will be completed in 2013 with the publication of the volumes describing the thermodynamic data for tin and iron (Part 1). The fourth phase of the TDB Project began in February 2008 and will continue into 2013. The focus of the fourth phase is to review the chemical thermodynamic data for inorganic compounds, as well as complexes of molybdenum and iron (Part 2), in order to update the review of the thermodynamic data for auxiliary species and to begin work on a review of the thermodynamics of cements. The initiation report on the thermodynamic data for cement materials has been completed. At the November 2012 TDB Project Management Board meeting, it was agreed that an initial report on the topic of actinide and brine chemistry in high ionic-strength systems should be prepared. Phase V of the TDB Project is currently under consideration.

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 (US DOE, 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 another Pitzer thermodynamic database (pitzer.dat) incorporated with the standard PHREEQC package and the SIT thermodynamic database, ThermoChimie (Duro et al., 2010).

A more extensive evaluation of the YMP Pitzer database, data0.ypf.R2, database was continued in 2012 in terms of comprehensiveness, consistency and accuracy, with emphasis on the comparison of the Pitzer model to the experimental data (e.g., solubility, activity and deliquescence relative humidity). 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. A technical report documenting these reviews will be issued in 2013.

Contact was made in 2012 with a German working group (Altmaier et al., 2011) developing a new database: the THEREDA (THErmodynamic Reference Database) Pitzer thermodynamic database. In 2013, a review will be conducted to determine if this database is suited to Canadian needs.

5.1.2.4 Gas Transport through Buffer

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

Version 2.0 of TOUGH2, a two-phase flow code, was selected and modified for LASGIT to simulate pressure-induced changes in properties, such as pore dilation. 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 (Gas Test 1) were analysed in 2009. The results were difficult to interpret, but seemed to indicate that gas dilation 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 were generated for Gas Test 2 (executed in 2009), which showed complex gas propagation behaviour in still partially saturated bentonite. The modelling was promising in its ability to represent gas breakthrough at the injection port; however, model gas propagation was too slow and diffuse, with gas appearing at the rock wall immediately opposite the injection port rather than at the opposite side of the container.

Several modifications to the model were recommended, including 1) modifications to the pressure-dependent permeability and capillary pressure functions, in order to improve the ability of the model to simulate a distinct pathway, and 2) inclusion of a heterogeneous stress boundary and stress-dependent permeability to simulate a gas pathway not immediately adjacent to the injection port. Future simulations will be conducted on Gas Test 3 (conducted in 2010), for which hydraulic data indicates fully saturated conditions. Gas Test 3 data are complex, with strong responses at the canister-bentonite interface, as illustrated in Figure 5.5. A technical report will be issued in 2013.

5.1.2.5 Shaft Seal Properties

The shaft seal for a deep geologic repository will include various materials with different functions. The reference material is a 70/30 bentonite/sand mixture. 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. Properties being measured include:

- Density of as-fabricated material;
- Porosity of as-fabricated material;
- Moisture content of as-fabricated material;
- Chemical composition of as-fabricated material;
- Swelling pressure under various reference groundwater conditions;
- Saturated hydraulic conductivity under various reference groundwater conditions;
- Gas permeability; and
- Mechanical properties.

Two independent laboratories were retained to carry out the analyses, and the final project deliverables are expected in 2013. Preliminary results indicate that the test results for hydraulic conductivity and swelling pressure are in accordance with the values predicted by Baumgartner (2006).

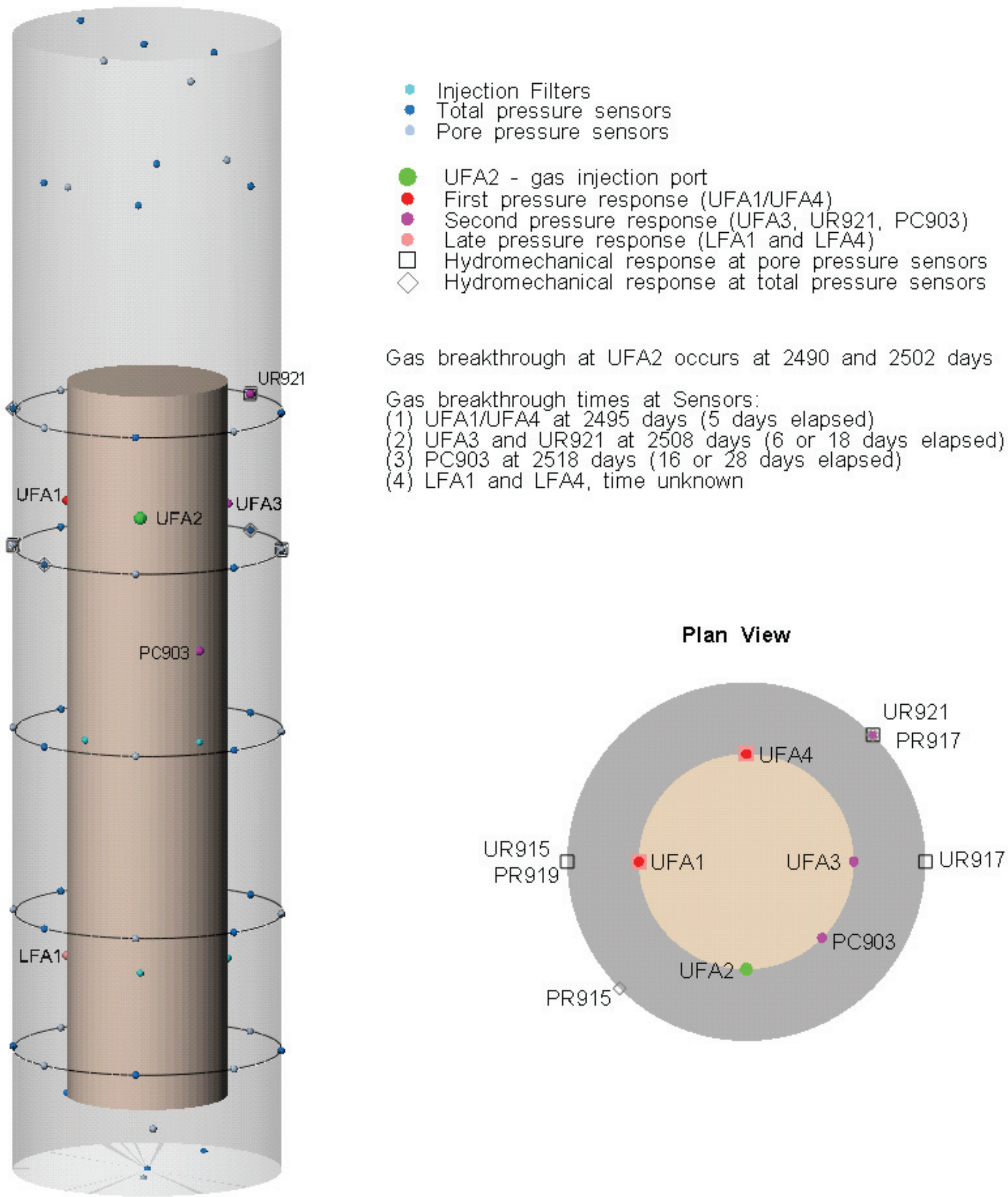

Figure 5.5: SKB LASGIT Gas Test 3 (2010 Gas Injection Tests) Showing Locations of Gas Injection (UFA2) and Gas Breakthrough.

5.1.3 Geosphere Modelling

5.1.3.1 Probabilistic FRAC3DVS-OPG and SYVAC3-CC4 Modelling

Safety assessments conducted by the NWMO use the following two computer codes.

- FRAC3DVS-OPG: used to generate detailed 3D deterministic finite-element predictions of groundwater flow and transport for a limited number of cases and for a limited number of radionuclides. Run times are quite long (hours to days) and the absence of a biosphere model means dose predictions cannot be obtained.
- SYVAC3-CC4: used to generate deterministic and probabilistic predictions of radionuclide releases to the environment. Run times are quite short (5 minutes) and a large number of radionuclides can be represented. A biosphere model is available and dose predictions can be obtained.

The SYVAC3-CC4 model is simplified and approximate when compared to the more sophisticated FRAC3DVS-OPG code; however, the long run times associated with the FRAC3DVS-OPG model preclude the use of this tool for probabilistic studies where, typically, 120,000 simulations are performed. With the advent of relatively inexpensive processing power and cluster or parallel computing, running detailed models probabilistically is becoming more feasible.

A work program was initiated in 2012 to test, using a proof-of-concept approach, the feasibility of conducting probabilistic simulations using detailed 3D numeric models. Existing models used in the safety assessment case study for a conceptual repository in crystalline rock (NWMO, 2012a) have been simplified and the modelling workflow automated to allow complete simulations to be executed under the control of a probabilistic sampling executive.

The groundwater flow portion of the simulations, executed relatively quickly, and the subsequent radionuclide transport simulations were executed in finite-difference mode. This reduced the memory requirement significantly and resulted in a total computation time of approximately 5 hours per simulation. Multiple simulations, run across a cluster of 46 processors, resulted in 500 fully probabilistic simulations completed in approximately 5 days.

Preliminary modelling results produced 1000 realizations of the system using a latin-hypercube sampling methodology. Five hundred of the simulations varied all model parameters probabilistically – 250 simulations fixed the geosphere parameters to their median values and varied all parameters related to the excavation damage zones, the shaft and the engineered barrier system; a further 250 simulations only varied parameters related to the engineered barrier materials. The regression analysis showed that the geosphere conductivity is the most important parameter for groundwater flow and transport within the hypothetical site. The well demand and the fracture conductivity were found to have a lesser impact on the discharge to surface. Figure 5.6 illustrates the results obtained for the first set of 250 simulations (as described above).

The preliminary results indicate that it might be feasible to use FRAC3DVS-OPG for probabilistic studies. The work program will continue in 2013 with an assessment of available cluster computing options.

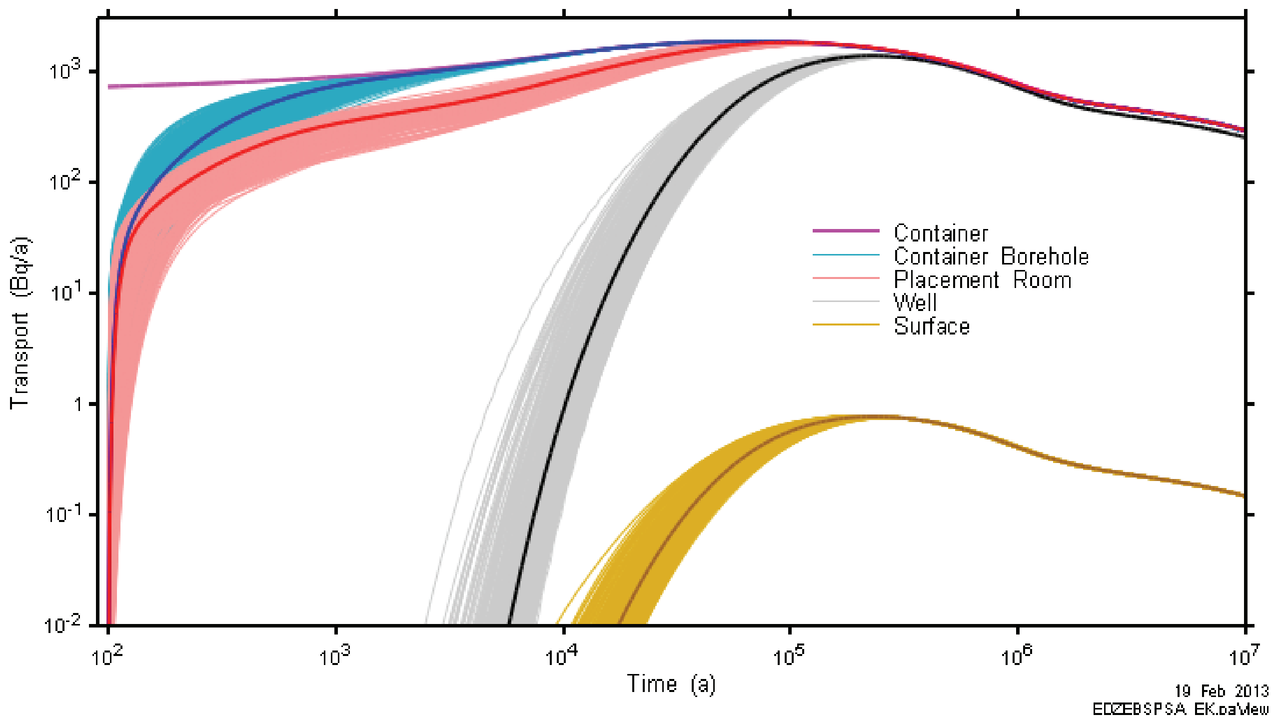

Figure 5.6: Excavation Damage Zone and Engineered Barrier System Transport Metrics

5.1.4 Biosphere Modelling

5.1.4.1 Human Intrusion Model

A model has been developed for the assessment of the consequences associated with inadvertent human intrusion into a used fuel DGR. The model (HIMv2.0) is based on a previous model (HIMv1.1) that was developed under the SYVAC-CC4 framework (D'Andrea and Gierszewski, 2004) for the Third Case Study Postclosure Safety Assessment (Gierszewski et al., 2004b).

HIMv2.0 considers inadvertent intrusion via a drilled borehole that intersects a container, bringing a portion of the used fuel directly to the surface. The dose consequences are calculated for two stylized exposure cases:

- A drill crew member, handling core debris and working near contaminated drill slurry (receiving a dose from inhalation, ingestion, groundshine and external irradiation); and
- A resident living in a house on contaminated soil (receiving a dose from groundshine, inhalation, soil and plant ingestion).

A technical report documenting the approach was published in 2012 (Medri, 2012a).

5.1.4.2 Non-Human Biota

In 2008, a screening methodology was developed for assessing the potential postclosure impact of a repository on specific representative non-human biota. The methodology involved the estimation of reference No-Effect Concentrations (NECs) for radionuclides in environmental media to which biota are exposed. Because of the conservative nature of the assumptions used to derive NECs, there was confidence that, despite uncertainty in environmental concentrations, there would be no significant ecological effect on biota as long as the NECs were not exceeded. The NECs were developed for a set of 12 radionuclides, including the major dose contributors identified in the Canadian Third Case Study and other safety assessments. The NEC approach is also used in the most recent safety assessment for a conceptual repository in crystalline rock (NWMO, 2012a).

In Europe, the calculation of dose consequences to non-human biota is largely performed using the ERICA approach (e.g., Torudd and Facilia, 2010). One of the significant differences between ERICA and the NECs is the approach used to model the partitioning behavior of a radionuclide between the media and the organism. ERICA uses concentration ratios, which estimate the concentration in an organism based on the concentration in the media (soil or water) in which it exists. The NEC approach uses transfer factors, which estimate the concentration in an organism based on the intake rate (of food, soil, water or sediment).

In 2012, the NWMO developed a non-human biota dose assessment model, which separately calculates dose consequences using the transfer factor approach (as with the NECs) and concentration ratio approach (as in the ERICA tool). The model considers the effects of 45 radionuclides on a wide range of species that are representative of the main taxonomic groups found in 3 different Canadian ecosystems (the southern Canadian Deciduous forest, the boreal forest and the inland tundra). A technical report documenting the approach will be published in 2013.

Because the topic of dose consequences to non-human biota is of current international and regulatory interest, NWMO will continue to monitor and conduct work activities in this area in upcoming years.

5.1.4.3 Aboriginal Lifestyle Characterization

The interests and concerns of Aboriginal peoples, as they pertain to a used fuel deep geological repository, are an integral part of the NWMO work program. Previous Canadian postclosure safety assessments have calculated doses to a hypothetical self-sufficient farming household living in the vicinity of the repository under temperate boreal conditions. Recognizing the need to consider time scales up to 1 million years, alternative exposure groups, with other diets and lifestyles, should be considered to ensure comprehensiveness of the safety assessment.

The purpose of this work program is to update existing Aboriginal lifestyle characterization data representative of the Boreal Forest and Inland Tundra, and to develop new data to characterize the Aboriginal lifestyle in the Southern Canadian Deciduous Forest. Key non-human biota species of importance to aboriginal communities are also to be identified. A technical report documenting the results will be issued in 2013.

5.1.4.4 Participation in BIOPROTA

BIOPROTA is an international collaborative program created to address key uncertainties in long-term assessments of contaminant releases into the environment arising from radioactive waste disposal. Participation is aimed at national authorities and agencies with responsibility for achieving safe and acceptable radioactive waste management practices, including both regulators and operators. Overall, the intention of BIOPROTA is to make available the best sources of information to justify modelling assumptions made within radiological assessments constructed to support radioactive waste management. In 2012, two projects receiving financial support from the NWMO were completed.

- Smith et al. (2012a) 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. The final report of the study provides an outline concept, which forms one possible approach to the demonstration of compliance with environmental protection objectives for radioactivity in the environment where available screening values are exceeded. Advice is provided also on how non-human biota assessments may be undertaken within performance assessments for disposal facilities for long-lived radioactive waste.
- Smith et al. (2012b) focused on the assessment of the dose to intruders arising as a result of drilling into a deep geological disposal facility for radioactive waste. The study examines: the technical aspects of why and how such intrusion might occur; considers how, and to what degree, exposure to the people involved would follow; identifies the processes which constrain the uncertainties; and develops and documents a reference approach for evaluation of the human intruder doses.

The NWMO is currently contributing to the following three projects, to be completed in 2013 and 2014.

<u>C-14 Project</u>

A program of work has been undertaken since 2009 with emphasis on the uncertainties around modelling the behaviour of C-14 in soils and in subsequent uptake by plants. This work concluded that the conceptualization of the dynamics of the plant canopy atmosphere influences the calculated plant C-14 concentrations, and the major source of uncertainty is related to the identification of conditions under which mixing occurs and isotopic equilibria are established. In 2012, a further work program was proposed to address the remaining uncertainties in soil-plant C-14 behaviour and to extend considerations to the behaviour of C-14 in aquatic environments.

The new work program will focus on the review of recent work related to soil-plant systems that has been funded by waste management organizations, together with other studies identified by project participants. The aim of the work is to peer review the studies and to consolidate the findings, enabling a robust understanding of the implications. The work program will also compile and summarize key features of models and data for assessing doses to humans via consumption of freshwater biota following C-14 long-term release to surface water bodies.

This project is financially supported by the NWMO, together with ANDRA and EDF (France), BfS (Germany), EPRI (USA), Nagra and ENSI (Switzerland), NDA RWMD (UK), NUMO (Japan), POSIVA (Finland), SKB and SSM (Sweden). The results from this work will be issued in a project report in 2013.

Non-Human Biota Temporal and Spatial Scales Project

This work program is designed to investigate the consequences of different assumptions for temporal and spatial scales when applied to long-term assessments of the radiological impact on representative species of wildlife. The project will deliver methodology documentation and supporting datasets to facilitate the application of spatially and temporally averaged media activity concentrations for estimating the postclosure impacts of radionuclides released from radioactive waste repositories on wildlife.

This project is financially supported by the NWMO, together with ANDRA and EDF (France), RWMD/NDA (UK), Nagra (Switzerland), NUMO (Japan), POSIVA (Finland), SKB and SSM (Sweden). The results from this work will be issued in a project report in 2013.

Geosphere-Biosphere Interface Project

This work program is designed to develop an improved and structured approach to characterizing and representing the interface between the geosphere and biosphere in long-term radiological impact assessment models.

This project is financially supported by the NWMO, together with ANDRA and EDF (France), RWMD/NDA (UK), NUMO (Japan), SKB and SSM (Sweden). Other organizations are also anticipated to participate in this project. The results from this work will be issued in a project report in 2014.

5.1.5 Integrated System Model

The postclosure safety assessment of a used fuel repository uses several complementary computer models, as identified in Table 5.2. These are either commercially maintained codes, or codes maintained by the NWMO under a software quality assurance program.

Table 5.2: Main Safety Assessment Codes for Postclosure Analyses

Software	Version	Description / Use
SYVAC3-CC4	9	Reference integrated system model
FRAC3DVS-OPG	1.3	Reference 3D groundwater flow and transport code
T2GGM	3.0	3D two-phase gas and water flow code
AMBER	5.5	Generic compartment modelling software
COMSOL	4.3a	3D multi-physics finite element modelling software
PHREEQC	2.17	Geochemical calculations code
MICROSHIELD	9.05	Radioactive shielding and dose code

The following sections describe code related activities conducted in 2012.

5.1.5.1 Updates to SYVAC3-CC4

The main software activity in 2012 was the release of the new integrated system model SYVAC3-CC4 v9 (NWMO, 2012b). The following changes were implemented into the new version.

- Address inconsistencies in how radionuclide content accumulates in sediment and overburden;
- Eliminate the need for code re-writing, re-compiling, and re-verification to accommodate changes in the geosphere site details; and
- Adjustment of the water source for domestic needs, livestock, and irrigation of fields (well, lake or combination of the above) so that water would be drawn from a well until the well's capacity is reached, and then surface waters would be used for additional demand.

The corresponding SYVAC3-CC4 Fourth Case Study dataset was issued in 2012 (Garisto et al., 2012). This dataset includes revisions to the following items relative to the previous version.

- Adsorption data for a variety of elements for sorption on granite, fractures, and engineered sealing materials;
- New data for the element instant release fractions from the fuel; and
- Improvements to the biosphere data for alignment with the Canadian Standards Authority (CSA) (2008).

5.1.5.2 Updates to mView

mView v4.10 is a scientific software package that provides support for model pre-processing (grid creation and property assignment) and post-processing (extracting further information from model results). The program is used to create input files for FRAC3DVS-OPG and T2GGM, in particular.

A work program was initiated in 2012 to update the mView software documentation to be compliant with NWMO-PROC-EN-002, R001 "Technical Computing Software" (NWMO, 2010). The documents targeted in the update were the mView verification report detailing the internal testing and code verification of each mView module and the mView User Manual. The verification report was issued as a Geofirma report in 2012 (Geofirma, 2012) and the User Manual is expected to be finalized early in 2013.

5.1.5.3 Updates to Miscellaneous Codes

New versions of several commercially available codes were also released in 2012 and installed on safety assessment computers, including AMBER v5.5, COMSOL v4.3a and MICROSHIELD v9.05.

5.2 SAFETY STUDIES

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

The focus of these studies is primarily on the postclosure period; however, some work activities on the preclosure period are proceeding also. The following sections describe work undertaken in both of these areas.

5.2.1 Postclosure Studies

5.2.1.1 Crystalline Rock Case Study

In 2012, a pre-project report was submitted to the CNSC (NWMO, 2012a) illustrating a used fuel repository conceptual design in crystalline rock and an associated postclosure safety assessment (referred to herein as the Crystalline Rock Case Study). The NWMO's primary objective for the pre-project review is to confirm that the illustrative postclosure safety assessment is consistent with CNSC Guide, G-320, on Assessing the Long Term Safety of Radioactive Waste Management (CNSC, 2006).

The Crystalline 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 (Gierszewski et al., 2004b) 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 used fuel container is assumed to consist of an outer copper vessel, an inner steel vessel, and three steel baskets. 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.

Once placed in the repository, the 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. The study considers both Normal Evolution and Disruptive Event scenarios, together with a range of associated sensitivity studies performed to illustrate the sensitivity of results to assumed degradations in the engineered and natural barriers. The results of both deterministic and probabilistic simulations are presented.

The work program resulted in the production of four auxiliary technical reports issued to support the postclosure safety assessment:

- Reference Data and Codes (Garisto et al., 2012);
- Features, Events and Processes (Garisto, 2012);
- Data for Radionuclide and Chemical Element Screening (Gobien and Garisto, 2012); and

- Human Intrusion Model for the Crystalline and Sedimentary Case Studies (Medri, 2012a).

5.2.1.2 Sedimentary Case Study

The Sedimentary Case Study is the next in the series of illustrative postclosure safety assessments. The purpose of this study is to determine the dose consequences associated with a deep geological repository situated in sedimentary rock. For this rock type, both copper shell and steel-only containers are under consideration.

The 2012 work activities included:

- Confirming appropriate characterization of the hypothetical geosphere and the conceptual repository design;
- Developing the groundwater flow model for the site, accounting for the repository excavations;
- Developing the system model for assessing dose consequences to a critical group living above the repository; and
- Completing the first round of gas generation and radionuclide transport modelling.

In the gas modelling work, 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 (LArge Scale Gas Injection Test) at SKB (Sweden).

The objective is to support the submission of a pre-project review report in 2013, similar to that made in 2012 for the Crystalline Rock Case Study (NWMO, 2012a).

5.2.1.3 NEA FEPS Update

Features, Events and Processes (FEP) provide a brief screening analysis for each performance assessment factor, indicating whether or not it should be included within the detailed safety assessment. Development of an internationally recognized FEP database is useful in that it helps ensure the NWMO FEP are consistent with international best practices.

In accordance with a decision made at the 2011 Integration Group for Safety Case (IGSC) annual meeting, the NEA accepted the proposed work activities to further develop the FEP database. In 2012, the NWMO provided funding to support this activity.

5.2.2 Preclosure Studies

5.2.2.1 Site Boundary for Surface Operations at a Deep Geological Repository

Postulated radiological emissions due to surface operations at a hypothetical DGR 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 of 1 mSv/a.

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 2012, additional work was completed to assess specific design sensitivities.

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.

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. Failure of the ventilation exhaust filtration system was considered as an Anticipated Operational Occurrence. Conservative estimates of the consequent public dose are, again, several orders of magnitude below the regulatory dose limit.

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 the regulatory limit.

5.2.2.2 Transportation Study

Used fuel destined for the DGR will have to be safely and securely transported from current interim storage facilities. In 2012, the NWMO issued a technical report (Batters et al., 2012) documenting the anticipated dose to members of the public arising from such transport.

The findings from this updated assessment provide a base case for NWMO as it plans a safe and secure transportation system, and will allow the CNSC to evaluate compliance with its regulations for protecting public health and safety. The findings from this update will be used to support mode and route analyses, and to define transportation system operating procedures.

In conducting this assessment, three road transport scenarios were identified which represent the range of pathways where the public potentially could receive levels of exposure or dose:

- Individuals residing or working along the transportation route;
- Drivers or passengers riding in vehicles stuck in traffic gridlock and sitting next to a truck carrying an UFTP; and
- Persons sharing a rest area with a truck carrying a UFTP.

Similar scenarios were assessed for rail transportation.

The analysis in this report is generic, based on representative assumptions at this stage of planning, where specific routes or geographic location of the repository site are unknown. The potential dose rates from the transport of used nuclear fuel are well below the CNSC regulatory limit and the dose received from natural sources.

5.2.2.3 MCNP Dose Calculations

The NWMO is often requested to provide dose estimates for various used fuel bundle and used fuel container shielding configurations. Such information is needed to support:

- Engagement activities, because questions about the nature of the hazard are often posed in specific terms by members of the public; and
- Engineering activities, because shield thicknesses are required for container design optimization.

The gamma component of the dose is readily generated in-house using the MICROSHIELD code; however, reliable estimates of the neutron component of the dose requires a more sophisticated code such as MCNP, a general-purpose Monte Carlo N-Particle code that can be used for neutron, gamma, beta, or coupled neutron/gamma/beta transport.

The purpose of this work is to characterize the neutron and gamma dose components for a set of used fuel bundle and container shielding configurations using MCNP modelling. The results of these calculations will serve as benchmarks for dose scaling in future calculation cases of interest. The work will be documented in a technical report in 2013.

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

A.1 NWMO Technical Reports

Batters, S., K. Tsang. U. Stahmer. Generic Transportation Dose Assessment. Nuclear Waste Management Organization Report NWMO TR-2012-06. Toronto, Canada.

Carvalho, J.L. Thermo-Mechanical Analysis of a Multi-Level Repository for Used Nuclear Fuel. Nuclear Waste Management Organization Report NWMO TR-2012-19. Toronto, Canada.

Freire-Canosa, J. Implications of Placing High Burnup Used Fuel in a Deep Geological Repository. Nuclear Waste Management Organization Report NWMO TR-2012-15. Toronto, Canada.

Garamszeghy, M. Nuclear Fuel Waste Projections in Canada – 2012 Update. Nuclear Waste Management Organization Report NWMO TR-2012-13. Toronto, Canada.

Garisto. F. Fourth Case Study: Features, Events and Processes. Nuclear Waste Management Organization Report NWMO TR-2012-14. Toronto, Canada.

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Kim, C.S., A. Man[1], D. Dixon, E. Holt[2] and A. Fritzell[3]. 2012. Clay-based for use in tunnel backfill and as gap fill in a deep geological repository: characterization of thermal-mechanical properties. Prepared by Atomic Energy of Canada Limited, [1]Golder Associates Ltd., [2]VTT Finland and [3]ES Konsult Sweden. Nuclear Waste Management Organization Report NWMO TR-2012-05. Toronto, Canada.

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NWMO. 2012b. SYVAC3-CC4 Theory, Version SCC409. Nuclear Waste Management Organization Report NWMO TR-2012-22. Toronto, Canada.

Sims, J. 2012. Review of Paleoseismological Methods for Seismic Hazard Assessment and Their Applicability to Central and Eastern Canada. John Sims and Associates. Nuclear Waste Management Organization Report NWMO TR-2012-25. Toronto, Canada.

Suckling, P[1]., J. Avis[2], N. Calder[2], P. Humphreys[3], F. King[4] and R. Walsh[2]. T2GGM Version 3.1: Gas Generation and Transport Code. [1]Quintessa Ltd., [2]Geofirma Engineering Ltd., [3]University of Huddersfield, [4]Integrity Corrosion Consulting Ltd. Nuclear Waste Management Organization Report NWMO TR-2012-23. Toronto, Canada.

Villagran, J.E. Used Fuel Container Retrieval from a Deep Geological Repository in Crystalline Rock Vertical Borehole Configuration. Nuclear Waste Management Organization Report NWMO TR-2012-03. Toronto, Canada.

Villagran, J.E. Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel. Nuclear Waste Management Organization Report NWMO TR-2012-18. Toronto, Canada.

Villagran. J.E and D. Marinceu. Used Fuel Container Retrieval from a Deep Geological Repository in Sedimentary Rock - Horizontal Tunnel Configuration. Nuclear Waste Management Organization Report NWMO TR-2012-17. Toronto, Canada.

Wolfaardt, G. M and D. R. Korber. Near-field Microbiological Considerations Relevant to a Deep Geological Repository for Used Nuclear Fuel – State of Science Review. Nuclear Waste Management Organization Report NWMO TR-2012-02. Toronto, Canada.

Wu, P. 2012. State-of-the-Science Review of the Stress Field during a Glacial Cycle and Glacially Induced Faulting. University of Calgary. Nuclear Waste Management Organization Report NWMO TR-2012-24. Toronto, Canada

A.2 Refereed Journal Publications, Conference Presentations & Invited Presentations

Avis J., Suckling P, Calder N., and Walsh R. 2012. T2GGM – A Coupled Gas Generation Model for Deep Geologic Disposal of Radioactive Waste. TOUGH2 Symposium 2012, Sept 17-19, Berkeley, USA.

Birch, K. "Overview of Engineering Design, Research & Development – The Long-Term Management of Canada's Used Nuclear Fuel". The Robert and Joyce Jones Speaker Series, Department of Civil Engineering, Queen's University, October 2012.

Celejewski, M., Al, T., Clark, I., McKelvie, J. An absorption method for porewater characterization in low permeability sedimentary rocks. Goldschmidt Conference, Montreal, June 24-29, 2012.

Christov, C., M. Zhang, S. Talman, E. Reardon and T. Yang. 2012. "Review of issues associated with evaluation of Pitzer interaction parameters", 2012 Goldschmidt Conference, Montreal, Quebec, Canada, June 24-29, 2012.

Gierszewski, P. Preparing for Canada's DGR projects. NEA Workshop on Issues for DGR Construction and Operation, Paris, France, 25-27 Jan 2012.

Hatton, C., Marinceu, D., Murchison, A. Use of Robotic Equipment in a Canadian Used Nuclear Fuel Packing Plant, 2nd International Conference on Applied Robotics for the Power Industry. IEEE-CARPI 2012-ETH Zurich, Switzerland. September, 2012.

Keech, P.G., S. Ramamurthy, P. Jakupi, J. Chen, D.W. Shoesmith, "Development and Corrosion Testing of Cold-Spray Cu Coatings for Canadian Used Nuclear Fuel Containers." International Society of Electrochemistry 63rd Annual Meeting, Prague, Czech Republic, Aug. 2012.

Marinceu, D. "Use of Robotic Equipment in a Canadian Used Nuclear Fuel Packing Plant", 2nd International Conference on Applied Robotics for the Power Industry, IEEE-CARPI 2012-ETH Zurich, Switzerland, September 2012

McKelvie, J. "An Overview of NWMO's Geoscience Activities in Support of a Deep Geological Repository for Used Nuclear Fuel". Guest Lecture in Earth Processes, Resources and the Environment, University of New Brunswick, 2012.

McKelvie, J. "Microbiological Considerations for the Performance of a DGR for used nuclear fuel". Guest Lecture, EESC15 Research Seminar in Environmental Science, University of Toronto Scarborough, 2012.

McKelvie, J., Sherwood Lollar, B., Wolfaardt, G., Korber, D. Assessing microbiological processes relevant to the development of a deep geological repository for used nuclear fuel. International Association of Hydrogeologists Congress, September 16-21, 2012. (Speaker)

Vinsot, A., Appello, C.A.J., Lundy, M., Wechner, S., Lettry, Y., Schwyn, B., McKelvie, J., Dewonck, S., Bossart, P., Delay, J. In situ diffusion test of hydrogen gas in the Opalinus Clay. International meeting "Clays in Natural and Engineered Barriers for Radioactive Waste Confinement", Montpellier, France, Oct. 22-25, 2012.

Conference Sessions Chaired

Mazurek, M. (University of Bern), Kennell, L. (NWMO), Hobbs, M. (NWMO). 22nd V.M. Goldschmidt Conference, June 24-29, 2012. Session: Assessing groundwater transport processes using natural geochemical tracers.

Waber, N. (University of Bern), McKelvie, J. (NWMO), Hirschorn, S. (NWMO). 22nd V.M. Goldschmidt Conference, June 24-29, 2012. Session: Geochemical and microbiological site characterization methods in low permeability and low porosity formations.

A.3 SCHOLARSHIPS

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

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 Cutoff Design. Queen's University. Supervisor Dr. Mark Diederichs.

Qureshi, Arif. An In-Depth Evaluation of the Used Fuel Transportation Package (UFTP)". University of Ontario Institute of Technology. Supervisor Dr. Edward Waller.

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

A.4 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

Alberta Innovates-Technology Futures (contractor)
AMEC NSS Limited
ANRIC Enterprises Inc.
Atomic Energy of Canada Limited (S. Stroes-Gascoyne)
ATS Automation
Babcock & Wilcox Canada
Candesco
Conestoga College
GeoEco Consulting 2010 (subcontractors).
Geofirma Engineering Limited
Golder Associates Ltd.
Integran Technologies Inc.
Integrity Corrosion Consulting Ltd. (Dr. Fraser King)
International Safety Research Inc.
McGill University (Professor Stephen Yue)
MegaStir Technologies Inc.
National Research Council Canada - Industrial Materials Institute (Boucherville, Quebec)
National Research Council Canada - Industrial Materials Institute (London, Ontario)
Novika Solutions
Royal Military College of Canada (Dr. G. Siemens)
Ryerson University (G. Wolfaardt)
SENES Consultants Limited
SKB International Consultants
TerraTek (Schlumberger)
University of Bern
University of British Columbia (Dr. S. Siddiqua)
University of Ottawa (Professor Bertrand Jodoin)
University of Saskatchewan (D. Korber)
University of Toronto (Professor B. Sherwood Lollar)
University of Toronto (Professor Don Davis)
University of Toronto (Professor Roger Newman)
University of Toronto (Professor Tony Sinclair)
University of Virginia (Professor John Scully)
University of Waterloo (subcontractor),
University of Western Ontario (Professor Dave Shoesmith)
University of Western Ontario (subcontractor) and
University of Windsor (Professor Roman Maev)
Virginia Polytechnic Institute and State University (Professor Marc Edwards)
Wilfrid Laurier University (Dr. R. Slawson)

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2012

ABSTRACT

Title: **Near-field Microbiological Considerations Relevant to a Deep Geological Repository for Used Nuclear Fuel – State of Science Review**
Report No.: **NWMO TR-2012-02**
Author(s): Gideon M. Wolfaardt[1] and Darren R. Korber[2]
Company: [1] Ryerson University and Stellenbosch Institute for Advanced Study
[2] University of Saskatchewan
Date: December 2012

A literature review-based study has been undertaken to evaluate the possible near-field impacts of microorganisms and their activity on a deep geological repository (DGR) for used nuclear fuel. The term "near-field" refers to the Engineered Barrier System (EBS) and those parts of the host rock in contact or near the EBS, whose properties have been affected by the presence of the repository. The EBS includes the buffer and backfill materials, as well as the used fuel containers.

In 2007, the Government of Canada selected *Adaptive Phased Management* (APM) as the approach for the long-term management of used nuclear fuel. The goal of APM is long-term containment and isolation of used nuclear fuel in a DGR, constructed in a suitable rock formation at a depth of approximately 500 metres. Consistent with international designs for nuclear waste repositories, the Canadian concept involves the use of steel or copper/steel containers, surrounded by a low-permeability, swelling clay buffer material. When considering the long-term performance of such an installation, the activity of microorganisms is relevant, along with the related effects of microbial activity on the engineered barriers. The implications of microorganisms in a deep geological repository on geochemical evolution, gas production, radionuclide transformation and transport, and EBS performance are reviewed in this report.

Given their ubiquity and metabolic capabilities, it is assumed that with sufficient time and appropriate conditions, microbes have the potential to impact the EBS, including the lifetime of used nuclear fuel containers through microbially influenced corrosion. Should this occur, containment of radioactive material would be provided by the used fuel itself, the clay-based sealing systems, and the enclosing host rock.

A challenge inherent to the evaluation of microbiological influences on the near-field repository environment is that long-term behaviour predictions must be based on short-term, and sometimes limited, data. Accordingly, a comprehensive understanding of the key microbiological parameters which could affect repository barrier components is necessary so that these factors can be incorporated, along with margins for error, into the repository safety case. It is also important that these microbiological parameters be described in the physical and chemical context of the EBS. Over the last 20 years, there has been significant advances in subsurface microbiology in the context of a DGR for used nuclear fuel. However, the number of established research groups with extensive experience in this sub-discipline is notably small relative to that of mainstream microbiology, and it needs to be determined how accurately the relatively unknown effects, and particularly the indirect effects, can be predicted based on the finite existing knowledge base. Further understanding of microbiology has the potential to refine long-term predictions regarding repository evolution and safety.

ABSTRACT

Title: **Used Fuel Container Retrieval from a Deep Geological Repository in Crystalline Rock Vertical Borehole Configuration**
Report No.: **NWMO TR-2012-03**
Author(s): J.E. Villagran
Company: Nuclear Waste Management Organization
Date: February 2012

This report describes a conceptual design for a used fuel container retrieval system and the container retrieval operation for a deep geological repository in crystalline rock. In the context of this report retrieval is the concrete action of removing used fuel containers from the repository. Retrievability is the ability in principle to recover used fuel containers once they have been placed in the repository, and implies making specific provisions in the repository design in order to make retrieval feasible should it be judged necessary.

The conceptual design for the repository consists of a network of shafts and tunnels that provide access to several panels of placement rooms where the used fuel containers are placed and sealed inside vertical boreholes drilled in the room floor.

The container retrieval system described in this report provides a conceptual description of the means to retrieve a used fuel container from its location in a repository placement room and to transfer it to the repository surface facilities. It makes use of the equipment used for the container placement operation and of mining equipment used for construction of the repository. The retrieval operation is essentially based on reversing the container placement operation, using the container transfer cask for subsequent transport of the retrieved container to the repository surface facilities. It also includes methods for removal of the concrete bulkheads and the engineered barrier materials surrounding the container.

Safety is a key consideration for the used fuel container retrieval operation. The conceptual design of the retrieval system equipment provides the required radiation shielding to allow unrestricted movement of personnel during operations. Monitoring of radiation fields and sampling of the underground environment can be conducted to ensure safety throughout the entire container retrieval operation.

ABSTRACT

Title: **Human Intrusion Model for the Fourth and Fifth Case Studies: HIMv2.0**
Report No.: **NWMO TR-2012-04**
Author(s): Chantal Medri
Company: Nuclear Waste Management Organization
Date: December 2012

The Human Intrusion Model for the Fourth and Fifth Case Studies (HIMv2.0) is a model for the assessment of the consequences from inadvertent human intrusion into a deep geologic repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a used fuel container in a repository and bringing used fuel debris to the surface.

HIMv2.0 calculates the dose consequences from two stylized exposure cases:

- a drill crew member from handling core debris and from contaminated drill slurry (exposure from inhalation, ingestion groundshine and external irradiation); and
- a resident living in a house on contaminated soil (exposure from groundshine, inhalation, soil and plant ingestion).

This report documents the basis for HIMv2.0, which was implemented on the AMBER software platform. It includes the model equations and software documentation.

The estimated peak doses for intrusion occur within a few hundred years of closure. For both case studies, peak doses are 1060 mSv per intrusion event for the drill crew member and 1140 mSv per year for the resident.

The probability of exposure is not estimated in this report. However, the probability of exposure for both scenarios would be small, and even more so for the resident since several very conservative assumptions are embedded in the stylization of the scenario (e.g., the resident is assumed to immediate start growing a garden at the drill site with the contaminated soil).

ABSTRACT

Title: **Clay-Based Pellets for Use in Tunnel Backfill and as Gap Fill in a Deep Geological Repository: Characterisation of Thermal-Mechanical Properties**
Report No.: **NWMO TR-2012-05**
Author(s): C-S. Kim[1], A. Man[2], D. Dixon[1], E. Holt[3], A. Fritzell[4]
Company: [1] Atomic Energy of Canada Limited, [2] Golder Associates Ltd. [3] VTT Technical Research Centre of Finland, Finland, [4] ES Konsult, Sweden
Date: December 2012

Pellets composed of bentonite-based materials are being considered by NWMO, Posiva and SKB for use in filling the rock-buffer annular gap in the In-Floor Borehole placement geometry, as a component in tunnel backfilling, and as a chamber filling material for the Horizontal Tunnel Placement (HTP) geometry. The range of locations where pellets could be used in a repository means that different types of pellets may be used since the primary functional requirements of the pellets will vary. Preliminary work has revealed that it is difficult to place pellets in repository simulation trials and achieve as-placed dry density of 1.4 Mg/m^3 and target thermal conductivity for this type of sealing material. Thermal conductivity of these materials tend to be low (generally <0.5 W/(m·K)), which limits the rate of heat transfer from the used fuel to the surrounding rock. This has implications on the temperature developed in a repository and the spacing of the used fuel to prevent excessive temperatures. Improving the thermal conductivity of clay-based pellet fill material is therefore highly desirable.

The objective of this work was 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, shapes and the effects of various volumetrically inert fillers on the properties of bentonite-based materials were examined. The pellets produced all had individual pellet densities in the order of 2.0 Mg/m^3. When loosely poured, the dry density of the fill typically was in the order of 1.1 to 1.2 Mg/m^3. This could be improved to ~1.4 Mg/m^3 using vibratory compaction. Pellets made with silica sand and illite additives had dry densities slightly higher than this. However, pellets containing additives have lower EMDDs than 100% bentonite which adversely affects their hydraulic conductivities and swelling pressures. The addition of Wyoming bentonite fines (i.e., 80 mesh granules), vibrated into the pore space between the pellets increased dry density to >1.5 Mg/m^3.

The presence of silica sand and illite in the pellets resulted in only a small increase in the measured thermal conductivity of a mass of dry pellets relative to pellets made with 100% bentonite. Increasing the overall density through vibratory compaction had a greater effect on increasing thermal conductivity than the additives. However, maximum values measured on pellets densified by vibratory compaction were close to 0.6 W/(m·K) and appears to be the maximum achievable for as-placed pellets without the addition of fines to the void space between the pellets or artificial wetting. This value can therefore be used as a lower bounding limit for thermal assessments of the in-floor borehole's gap fill in the KBS-3V geometry as well as tunnel backfill where there is no immediate water influx (dry borehole). The vibration of Wyoming bentonite fines (80 mesh granules) into a pellet-filled volume typically provided a slight improvement to the thermal conductivity to slightly less than 0.7 W/(m·K).

ABSTRACT

Title: **Generic Transportation Dose Assessment**
Report No.: **NWMO TR-2012-06**
Author(s): S. Batters[1], K. Tsang[1], U. Stahmer[2]
Company: 1- AMEC NSS LTD, 2 - NWMO
Date: October 2012

Canada, following a comprehensive decision making process, has chosen to develop a deep geological repository for the long term management of its used nuclear fuel. That used fuel will have to be safely and securely transported from its current interim storage facilities to the repository. The Nuclear Waste Management Organization (NWMO) is responsible for the transportation of the used fuel and has completed an update of an existing Dose Assessment Report.

The updated information will assist NWMO in evaluating the impact that transport of used nuclear fuel will have on the public and the environment. The findings from this updated assessment will provide a base case for NWMO as it plans a safe and secure transportation system, and will allow the Canadian Nuclear Safety Commission (CNSC) to evaluate compliance with its regulations for protecting public health and safety. The findings from this update will be used to support mode and route analyses, and defining transportation system operating procedures.

The Used Fuel Transportation Package (UFTP) is the reference transportation package for this updated assessment. NWMO is using the UFTP for its reference case in planning and engineering the repository design. NWMO, in order to perform a diligent assessment, conducted an analysis of potential doses that could be received by the public during road and railroad transport and for a hypothetical accident scenario.

In conducting this assessment, three road transport scenarios were identified which represent the range of pathways where the public potentially could receive levels of exposure or dose.

Individuals residing or working along the transportation route
Drivers or passengers riding in vehicles stuck in traffic gridlock and sitting next to a truck carrying an UFTP, and
Persons sharing a rest area with a truck carrying a UFTP.

Similar scenarios were assessed for rail transportation.

The analysis in this report is generic, based on representative assumptions at this stage of planning where specific routes or geographic location of the repository site are unknown. The information will assist NWMO to assess the general level of exposure to the public from the UFTP operating under normal transportation conditions and to highlight opportunities where NWMO can incorporate ALARA principles to further reduce the exposure to the public.

The analysis is not intended to provide an exhaustive analysis of any specific set of scenarios. Scenarios can be defined that could result in different dose levels than those presented in this report. However, a detailed assessment of transportation impact scenarios is premature until such factors as repository location, transportation mode and routes, population densities, transport package design, etc. are known.

The CNSC radiation dose limit for a member of the public was used to interpret the results of this assessment. The annual maximum dose or exposure rate to the public is specified in the regulations as 1 milliSievert per year (1 mSv/y). To put this number into perspective, the average Canadian receives approximately 1.8 mSv from background or natural radiation sources each year, and the dose from an abdominal X-ray is approximately 0.7 mSv.

A summary of the annual dose which a representative person[1] could receive, based on typical transportation scenarios, is shown in Figure S-1. The CNSC regulatory limit and average annual dose from natural background radiation sources in the environment is shown.

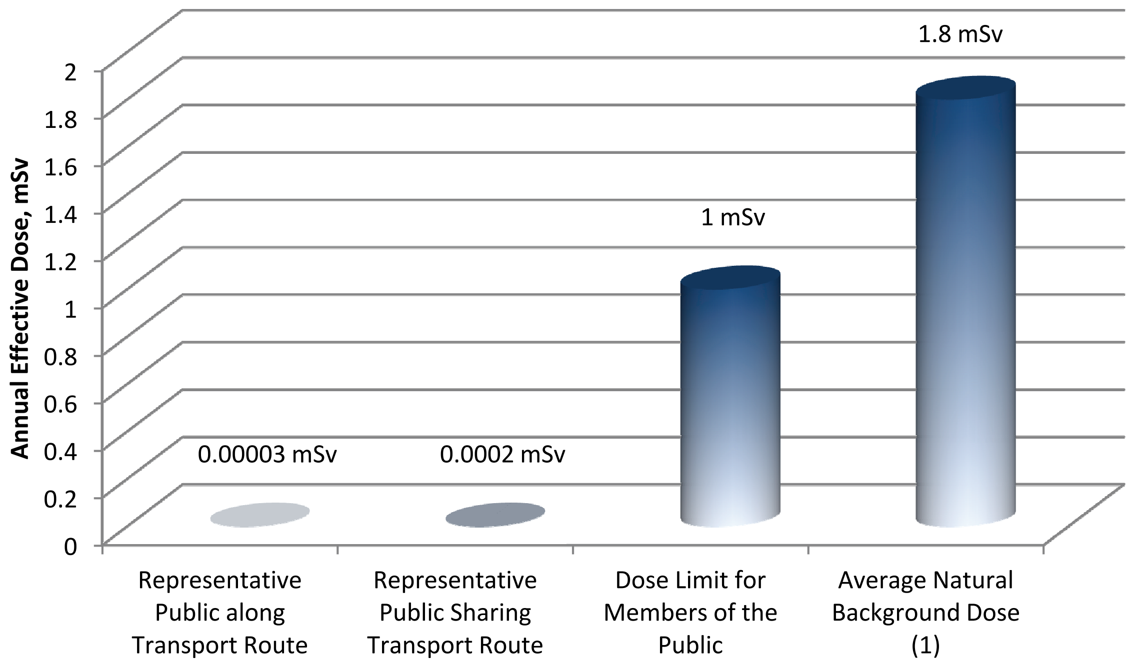

Figure S-1: Comparison of Dose to a Member of the Public

The potential dose rates from the transport of used nuclear fuel are well below the CNSC regulatory limit and the dose received from natural sources.

In completing the assessment of potential exposure to the general public, a hypothetical, yet highly unlikely, accident scenario was described and evaluated. This involved a potential release of radioactive material from the UFTP. Again, the standards established by the CNSC were used to conduct the assessment. The potential dose received by a person located near the accident was found to be dominated by direct external radiation exposure from the used fuel inside the transport cask. The dose contribution from potential releases was negligible in comparison.

[1] Recently, the International Commission on Radiological Protection defined the ‘representative person’ as an individual with characteristics that reflect those of the group that receives the highest doses from a particular source for a given radionuclide. The representative person is equivalent to, and replaces, the ‘average member of the critical group’, which was previously used as the basis for determining compliance with dose constraints for the public. This new terminology emphasizes that the value is based on a dose calculation for a person, who is almost always a hypothetical construct, since no actual person corresponds precisely to the group average.

In all cases, the maximum individual dose to the public under routine transport and accident conditions assessed was found to be less than the CNSC regulatory limit of 1 mSv per year. The public dose values calculated compare well with international experience.

Reference:

1. Average Natural Background Dose: Grasty, R.L. & LaMarre, J.R. 2004. The Annual Effective Dose from Natural Sources of Ionising Radiation in Canada. Radiation Protection Dosimetry (2004), Vol. 108, No. 3, pp. 215-226.

ABSTRACT

Title: **Simulation of the Anaerobic Corrosion of Carbon Steel Used Fuel Containers Using the Steel Corrosion Model Version 1.0 (SCM V1.0)**
Report No.: **NWMO TR-2012-07**
Author(s): Fraser King[1] and Miroslav Kolar[2]
Company: [1] Integrity Corrosion Consulting Limited, [2] LS Computing Limited
Date: May 2012

The results of preliminary simulations performed using the Steel Corrosion Model Version 1.0 (SCM V1.0) are presented and discussed. The SCM V1.0 simulates the anaerobic corrosion behaviour of carbon steel containers in a deep geological repository in sedimentary host rock and the impact of corrosion products on other barriers in the repository. The model is based on a series of one-dimensional reactive-transport equations that describe the various mass-transport, redox, adsorption/desorption, precipitation/dissolution, and chemical speciation processes of each of the thirteen chemical species considered in the model. Solution of these equations involves the use of a mixed-potential model based on the electrochemical reactions involved in the corrosion of the container, from which the time dependent corrosion rate and corrosion potential can be predicted, leading to an estimate of the container lifetime. An important aspect of the corrosion behaviour is the formation of a precipitated corrosion product film that blocks the surface interfacial reactions and inhibits the transport of reactants to, and of corrosion products away from, the corroding interface. The effects of slow saturation of the repository as a result of the low hydraulic conductivity of the sedimentary host rock are also taken into account.

In addition to the corrosion reactions, the model also simulates the interaction of dissolved Fe(II) ions with the bentonite clay. Those interactions may involve the adsorption of Fe(II) on the clay by ion exchange, alteration to non-swelling berthierine clay, and/or blockage of the bentonite pore volume by the precipitation of corrosion product. The generation, transport, and release of hydrogen is simulated in a simplified manner.

So-called Base Case simulations have been performed for both shale and limestone host rocks, the two cases differing in the host rock thermal properties and calcite content. The sensitivity of the predicted repository performance to certain input parameters and model assumptions was also investigated, in particular the effect of the assumed repository saturation period, the values of threshold relative humidity values that control the rates of the surface electrochemical reactions, and the assumed minimum porosity for precipitated corrosion products.

The Base Case simulations using best-estimate values of the various input parameters predict lifetimes of 11,200 to 36,500 a for carbon steel containers with a corrosion allowance of 1 to 3 cm. Extensive precipitation of corrosion product (in the form of magnetite) occurs within a few tens of cm of the container, but minimal clay alteration is predicted. The results and capabilities of the SCM are compared with both corrosion rates from laboratory and archaeological analog studies and predictions from other similar models described in the literature. Areas for further development of the model and key pieces of missing mechanistic understanding and experimental data are identified

ABSTRACT

Title:	**Fourth Case Study: Reference Data and Codes**
Report No.:	**NWMO TR-2012-08**
Author(s):	F. Garisto, M. Gobien, E. Kremer and C. Medri
Company:	Nuclear Waste Management Organization
Date:	November 2012

The Fourth Case Study is an illustrative postclosure safety assessment of a conceptual repository for nuclear used fuel located at 500 m depth at a hypothetical site on the Canadian Shield.

The conceptual design differs from the Third Case Study in that it considers vertical in-floor borehole placement of used fuel containers (UFCs) rather than the horizontal or in-room placements investigated previously. The reference UFC design has also been updated: it retains the outer copper shell for corrosion protection and inner steel vessel for structural support; however, the capacity of the UFC has increased from 324 to 360 fuel bundles.

While the hypothetical site where the repository is excavated is the same as in the Third Case Study, the exact location has shifted approximately 1500m to the north east and the depth has changed from 670 m below ground surface (mBGS) to 500 mBGS. Furthermore, the geosphere has been assigned different properties.

The main safety assessment codes used in the Fourth Case Study are:

- FRAC3DVS-OPG – for 3D groundwater flow and radionuclide transport;
- RSM – a simple screening model used to identify the key radionuclides;
- SYVAC3-CC4 – the primary safety assessment system model (container, repository, geosphere, biosphere);
- HIMv2.0 – for calculating dose consequences for the human intrusion scenario.

These codes and their datasets are maintained under a software quality assurance system at NWMO. The codes are described briefly in this report.

The reference datasets are based on a combination of the site conceptual model information and the repository design description, with most of the general material properties and other input parameters adopted from the previous work, updated where available by more recent studies. This report provides a summary of all the data selected, and indicates the references where more details about the derivation of the data may be found.

ABSTRACT

Title:	**Corrosion of Nuclear Fuel (UO_2) Inside a Failed Nuclear Waste Container A Review of Research Conducted Under the Industrial Research Chair Agreement Between NSERC, NWMO and Western University (January 2006 to December 2010)**
Report No.:	**NWMO TR-2012-09**
Author(s):	Heming He, Michael Broczkowski, Kevin O'Neil, Derrick Ofori, Oleg Semenikhin and David Shoesmith
Company:	Western University
Date:	May 2012

This report reviews the research conducted over the second term (2006 to 2010) of an industrial research chair established to determine the behaviour of CANDU fuel wastes inside a failed waste container. Research was concentrated in three areas: (i) the influence of fuel properties on its corrosion; (ii) the possibility of local chemistries, particularly low pH, within corrosion product deposits and flaws in the fuel, and (iii) the influence of dissolved H_2, from steel corrosion, on the fuel corrosion process. A range of experimental techniques was employed including electrochemical methods, Raman spectroscopy, X-ray photoelectron spectroscopy, atomic force and current-sensing atomic force microscopy, and secondary ion mass spectrometry.

A review of spent fuel properties indicated that the key in-reactor modifications of the properties of uranium dioxide most likely to influence its corrosion are: (i) rare-earth doping of the UO_2 matrix, (ii) the production of noble metal particles, and (iii) the introduction of non-stoichiometry.

Rare-earth doping was found to have a small influence in suppressing fuel corrosion; although the mechanism by which this occurs remains to be investigated. The introduction of non-stoichiometry was found to have a major influence on fuel reactivity which increased by over a factor of 1000 over the range x = 0.002 to x = 0.23 (in UO_{2+x}). This increase was attributable to the formation of defect clusters as the degree of non-stoichiometry increased. Since the increase in non-stoichiometry due to the in-reactor production of excess oxygen is likely to be confined to $x \le 0.007$, only a small increase in chemical reactivity (a factor of ≤ 5) of the fuel is anticipated.

Previous model calculations predicted that the development of acidic conditions in occluded regions of the fuel surface would be negligible. These predictions were verified in a series of experiments which simulated, as closely as feasibly possible, the anticipated surface conditions, and indicated acidification at the alpha radiation dose rates anticipated was extremely unlikely. These studies included experiments to assess the consequences of exposure to low pH on fuel dissolution and peroxide reduction.

Noble metal particles were shown to act as catalytic anodes for H_2 oxidation thereby suppressing fuel corrosion by the galvanic coupling of these particles to the rare earth doped conductive UO_2 matrix. Since these particles can also act as catalytic cathodes for H_2O_2 reduction and, hence, accelerate fuel corrosion via a similar galvanic-coupling process, their influence when both H_2O_2 and H_2 were present was also investigated. For 1.5 at% SIMFUEL (which approximately simulates anticipated CANDU fuel burn-ups) complete protection of the fuel surface from corrosion could be achieved providing the aqueous H_2/H_2O_2 concentration ratio was $> 10^6$.

ABSTRACT

Title: **Data for Radionuclide and Chemical Element Screening**
Report No.: **NWMO TR-2012-11**
Author(s): M. Gobien and F. Garisto
Company: NWMO
Date: December 2012

Containment and isolation in a deep geologic repository is one approach for the long-term management of used CANDU fuel.

Used nuclear fuel stored in the repository contains hundreds of different radionuclides arising from fission, neutron activation and decay processes. The fuel also contains many chemical elements that are potentially chemically hazardous (e.g., As and U).

However, there is considerable variation in the ability of these various contaminants (radionuclides or chemical elements) to cause harm to humans and the natural environment. Therefore, a simpler screening model can be used to reduce the number of contaminants considered in a detailed postclosure safety assessment for a used fuel repository. For a specific repository design and site, the screening model identifies those radionuclides and chemical elements that would not lead to significant harm (radiological or otherwise) and, hence, that would not require further detailed evaluation.

However, to support such a screening model necessarily requires basic information on a large number of radionuclides and chemical elements. This report describes the data that are needed for screening analyses of those postclosure scenarios in which the main conduit by which contaminants reach the surface is via transport in groundwater. The data included in the report are listed in Section 1.

ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2012 Update**
Report No.: **NWMO TR-2012-13**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2012

Since the Nuclear Waste Management Organization submitted its Final Study in 2005, there have been a number of completed and planned nuclear refurbishments as well as proposed 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 2011 report [Garamszeghy, 2011] and summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2012 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, 2012, a total of approximately 2.35 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 74,000 bundles from the 2011 report. For the existing reactor fleet, the total projected number of used fuel bundles produced to end of life of the reactors ranges from about 3.0 to 5.2 million used CANDU fuel bundles (61,000 t-HM to 104,000 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 most reactors are refurbished and life extended for an additional 25 EFPY of operation. This represents a slight decrease in the forecasts from the 2011 report due to the decision to shutdown the Gentilly-2 reactor at the end of 2012.

Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the current reference scenario projects a total of 4.4 million bundles. For design and safety assessment purposes, the NWMO has conservatively assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet.

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 unchanged from the 2011 report.
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: **Fourth Case Study: Features, Events and Processes**
Report No.: **NWMO TR-2012-14**
Author(s): F. Garisto
Company: Nuclear Waste Management Organization
Date: November 2012

The Fourth Case Study is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical site in the Canadian Shield. It differs from the previous Third Case Study in that it considers a repository holding 4.6 million used fuel bundles (rather than 3.6 million), a revised repository design, a different repository depth (500 m rather than 670 m), and a hypothetical repository site with different characteristics.

The reference container has an outer copper shell for corrosion protection, an inner steel vessel for structural support, and a capacity to hold 360 used fuel bundles. The containers are placed with an in-floor placement design, whereas in-room placement or horizontal borehole placement was considered in the Third Case Study. The repository is located at the same hypothetical site as in the Third Case Study, but with different fracture and rock properties. The repository is placed at a depth of 500 m as a design assumption.

The safety assessment of a repository must consider a broad range of factors that could potentially affect the behaviour of the repository, contaminants arising from it and its environment over the periods of interest. These factors may be features of the repository or site (e.g., waste type, repository depth), events (e.g., earthquakes, climate change) or processes (e.g., sorption), and are known collectively as FEPs. They are used as input for scenario identification and subsequent conceptual model development for the safety assessment.

However, not all potential FEPs are necessarily included in a given safety assessment. Thus, this report provides a structured and comprehensive list of possible FEPs relevant to the Fourth Case Study design and site. For each FEP, this report:

- provides a brief description of the FEP;
- discusses its relevance to the Fourth Case Study repository system; and
- identifies the scenarios where relevant FEPs are considered within the conceptual models developed for the Fourth Case Study.

The development of a safety case for a site-specific safety assessment would proceed in stages from conceptual to detailed studies. The Fourth Case Study is a scoping study and is based on a hypothetical repository and site. The present FEPs assessment is representative of the level of information and analysis that would be available during the early stages of siting.

ABSTRACT

Title:	**Implications of Placing High Burnup Used Fuel in a Deep Geological Repository**
Report No.:	**NWMO TR-2012-15**
Author(s):	Jose Freire-Canosa
Company:	Nuclear Waste Management Organization
Date:	December 2012

The Nuclear Waste Management Organization is examining the implications of high burnup fuel in the design of a deep geological repository.

In assessing any implications, this study was completed by assuming that the fuel to be stored is high burn-up fuel from an EPR advanced reactor with a mean burn-up of 50 MWd/kg U. Data available in the open literature from the Finnish Program were used and extrapolated to relevant Canadian geological conditions using gneiss rock for the EPR DGR design.

The EPR DGR design has the same layout as the CANDU repository with an identical number of placement tunnels. The storage capacity of the EPR DGR (21,075 EPR fuel assemblies) is based on the number of assemblies that would generate the same amount of electricity (about 4,930 TWh_e) as the 3.6 million CANDU fuel bundles to be stored in a reference CANDU repository. This requires that the number of used fuel containers for the CANDU DGR (10, 000) is nearly doubled those for the EPR DGR (5,270).

The footprint of the DGR is primarily dependent on the decay heat load from the fuel in the used fuel containers, the distance separating adjacent placement tunnels, and, the heat transfer properties of the engineered barriers and the rock. Based on a maximum used fuel container surface temperature of 81°C, the minimum spacing of the EPR containers in a CANDU DGR is estimated at 8.0 m when the distance separating the placement tunnels is 40 m. This compares with a borehole spacing of 4.2 m for the reference CANDU fuel repository. The longer distance between boreholes for the EPR fuel is mainly due to the higher heat load of their used fuel container (1830 W) over the CANDU fuel container (1285 W). Even though the spacing between the boreholes is doubled for the EPR fuel, the layout area and the length of the tunnels for the EPR DGR are nearly identical to the reference CANDU DGR.

The main difference between the two DGRs is the greater number of used fuel containers, nearly doubled for the CANDU fuel. The smaller cross section of the EPR placement tunnels also reduces the excavation effort. Reducing the distance separating the placement tunnels, increased the excavation efforts for the EPR DGR.

ABSTRACT

Title:	**Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock**
Report No.:	**NWMO TR-2012-16**
Author(s):	NWMO
Company:	Nuclear Waste Management Organization
Date:	December 2012

The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally-approved plan for safe long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

The repository and its surroundings comprise a system that is designed to protect people and the environment through multiple barriers. These barriers include the ceramic used fuel, long-lived corrosion resistant containers, engineered sealing materials and the surrounding geosphere.

Safety is a priority for the implementation of the APM program. To support the focus on safety, the NWMO conducts a wide range of complementary activities, including research, design development, technology demonstration and safety assessment, which are necessary to assess the performance of the multi-barrier repository concept at timeframes relevant to illustrating long-term safety.

A site selection process is currently underway to identify a safe site in an informed and willing host community. The process of site selection will take several years. As potentially suitable sites are identified with interested communities, detailed field studies and geoscientific site characterization activities will be conducted to assess whether the APM multi-barrier repository concept could be safely implemented to meet rigorous regulatory requirements.

At this very early stage in the process, before specific sites have been identified for examination, it is useful to conduct generic studies to illustrate the long-term performance and safety of the multi-barrier repository system within various geological settings.

This report provides an illustrative case study of the current multi-barrier design and postclosure safety of a deep geological repository in a hypothetical crystalline Canadian Shield setting. The purpose of this case study is to present a postclosure safety assessment methodology to illustrate how Canadian Nuclear Safety Commission (CNSC) expectations, documented in CNSC Guide G-320, Assessing the Long Term Safety of Radioactive Waste Management, are satisfied. For a licence application for a candidate site, a full safety case would be prepared that would include more information on the design and postclosure safety, as well as a detailed description of the geosphere, an environmental assessment, and an operational safety assessment.

Geosphere

A hypothetical geosphere was derived, in part, from historic experience gained in the Canadian Nuclear Fuel Waste Management Program. It was developed for the purpose of this illustrative case study while the NWMO proceeds with the APM siting process and selection of a preferred site in an informed and willing host community. While the hypothetical site represents one

example of a possible crystalline rock setting, a range of characteristics are described for alternative settings that are considered in the safety assessment to both illustrate an approach to assess long-term safety and the functionality of various barrier systems.

The long-term safety and performance of a used fuel repository will rely in part on the geologic setting that surrounds the repository. The geosphere will provide a geomechanically and geochemically stable environment. Geomechanical stability enables safe excavation and placement of the containers and engineered barrier system, and isolates the containers from a wide range of future human and natural events. A stable geochemical environment supports the container durability and minimizes radionuclide mobility. The ability of the geosphere to support these attributes will be dependent on site-specific conditions.

For the purposes of this illustrative assessment, the hypothetical geosphere is divided into three groundwater systems, which are assumed to have the following characteristics:

1. The shallow groundwater system, located near surface between 0 and 150 m below ground surface, is predominately driven by local and sub-regional scale topographic changes. The groundwater velocities in the shallow zone are sufficiently high that mass transport is primarily by advection. The groundwater in this zone is fresh and oxygen-rich with a low total dissolved solids concentration.
2. The intermediate groundwater system between 150 and 700 m below ground surface is a transition zone from fresh and oxygen-rich to more mineralized and becoming chemically reducing with depth. At the hypothetical site, the shift from oxidizing to reducing conditions occurs at a depth of about 150 m. In the intermediate groundwater system, larger domains of low permeability rock tend to decrease mass transport rates.
3. In contrast with the shallow and intermediate groundwater systems, the groundwater in the deep system below 700 m has a higher total dissolved solids concentration and fluid densities, and is under chemically reducing conditions. The groundwater velocity in the rock mass is very small.

Design Concept

The current conceptual design for crystalline rock consists of a repository constructed at a depth of approximately 500 m below surface. The repository contains a network of placement rooms with in-floor boreholes for the base case inventory of 4.6 million used fuel bundles encapsulated in about 12,800 long-lived used fuel containers. The container design consists of a copper outer vessel, or shell, that encloses a steel inner vessel. The outer copper shell provides effective resistance to container corrosion under deep geological conditions, while the inner steel vessel provides strength for the container to withstand expected hydraulic and mechanical loads, including earthquakes and glaciation.

Each borehole in the floor along the placement room centerline has a used fuel container surrounded by a clay-based sealing material of highly-compacted bentonite buffer disks, rings and gap-fill pellets. The placement room above the boreholes is filled with backfill materials such as a bentonite/sand mixture and other sealing materials. Bentonite and sand are durable natural materials that are expected to maintain their properties over the long term. Bentonite is a type of clay that swells on contact with water, resulting in its natural self-sealing property.

Postclosure Safety Assessment

The primary safety objective for the deep geological repository is the long-term containment and isolation of the used nuclear fuel. The safety of the repository would be based on a combination of the geology, engineered design, careful operations, and quality assurance processes including review and monitoring. Safety assessment provides a quantitative evaluation of the overall performance of the repository system and its impact on human health and on the environment. In this respect it is able to identify features or processes that contribute to an understanding and confidence in long-term repository safety.

This illustrative case study focuses on long term or postclosure safety. This is the period after the repository has been filled with used fuel containers, and has been sealed off and closed. Consistent with CNSC Guide G-320, the study identifies scenarios, models and methods for evaluating safety, with which to assess dose consequences and the influence of uncertainties. The results are compared against interim acceptance criteria for protecting persons and the environment.

The assessment does not try to predict the future, but instead examines the consequences for a range of scenarios, from likely to unlikely to “what if”. The likely scenarios are considered under the heading of “Normal Evolution Scenario.”

Normal Evolution Scenario

The normal evolution scenario presented in this report is based on a reasoned extrapolation of the reference case site and repository characteristics over time, consistent with the expectations of CNSC Guide G-320. The report describes why the used fuel copper containers are expected to remain intact over the timeframe of interest. For the purpose of the reference case normal evolution scenario, a small number of containers are assumed to be placed in the repository with undetected defects in the copper shell. Conservatively, these containers are assumed to be positioned within a placement room associated with the shortest travel time through the geosphere to the surface biosphere. The anticipated effects of glaciations on the assessment are also described.

The postclosure safety assessment adopts scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or future site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted and documented to allow the impacts of uncertainties to be bounded.

For the reference case safety assessment, the primary contributor to the public dose over the long term from an assumed small number of defective used fuel containers is the instant release fraction of Iodine-129, a long-lived radionuclide in used fuel that is non-sorbing in the geosphere. The calculated peak dose for the reference case is about 910 times lower than the interim dose acceptance criterion of 0.3 mSv per year for the normal evolution scenario and occurs at about 100,000 years after closure. The long time to peak dose is due, in part, to the combined performance of the repository barrier systems including the robustness of the long-lived containers, the integrity of the engineered sealing systems and the near-field rock surrounding the repository.

Sensitivity Analyses and Bounding Assessments

Recognizing that there are uncertainties associated with the future evolution of a repository, the NWMO has varied a number of important parameters and assumptions, completed bounding assessments and has developed a number of hypothetical “what-if” scenarios to explore the influence of parameter and scenario uncertainty in assessing long-term safety. This approach is consistent with CNSC Guide G-320 on the use of different assessment strategies.

Key parameters that could potentially affect long-term safety are varied in sensitivity cases to understand the impact of uncertainties in these parameters:

- An increase in fuel dissolution rate by a factor of 10;
- An increase of radionuclide instant release fractions to 10%;
- A range of rock mass hydraulic conductivities that cover a factor of 1,000;
- A decrease in distance between the repository and an assumed transmissive fracture from 25 m to 10 m;
- An increase in container degradation by increasing the assumed undetected container defect area by a factor of 10; and
- A decrease in geosphere sorption with a coincident increase in radionuclide solubility limits.

Some parameters are also pushed beyond the reasonable range of variations in bounding assessments. In these cases, parameters are completely ignored by setting their values to zero or by removing physical limits for the following:

- An increase in radionuclide solubility in groundwater by ignoring solubility limits;
- A decrease in radionuclide sorption in the geosphere by ignoring sorption; and
- A decrease in radionuclide sorption in the near field by ignoring sorption.

The results from the sensitivity analysis and the bounding assessments conducted as part of this illustrative case study are shown in Figure E1.

The sensitivity analyses show that the impact on dose is small when key parameters are varied. As shown in Figure E1, the parameter with the most significant impact on dose is from the dissolution of ceramic used fuel. This is because the bulk of the radionuclides are retained within the used fuel, which is a low-solubility solid. The dose consequence when the fuel dissolution is increased by a factor of 10 is assessed to be 7.3 times greater than the reference case value.

The bounding assessments show a noticeable increase in dose when sorption in the geosphere is ignored, as well as when sorption in the near field is ignored (see Figure E1). When sorption is ignored in the geosphere, peak dose is increased to 210 times the reference case value and occurs at ~48,000 years (versus 100,000 years in the reference case).

Recognizing the importance of parameters such as used fuel dissolution and sorption as shown in this case study, NWMO maintains active research programs in these areas to continue to improve our understanding of these processes. Nevertheless, the peak dose rate to a member of the public is still estimated to be about 130 times lower than the interim dose acceptance criterion of 0.3 mSv per year.

All the previous results were obtained through deterministic analyses. A further understanding of uncertainties can be obtained through probabilistic modelling. In the present illustrative case study, a probabilistic analysis was conducted on the contaminant release and transport parameters. A total of 120,000 simulations were examined to identify a 95th percentile peak dose rate. The dose consequence in this case is assessed to be 4 times greater than the reference case. This remains 230 times below the interim dose acceptance criterion of 0.3 mSv per year.

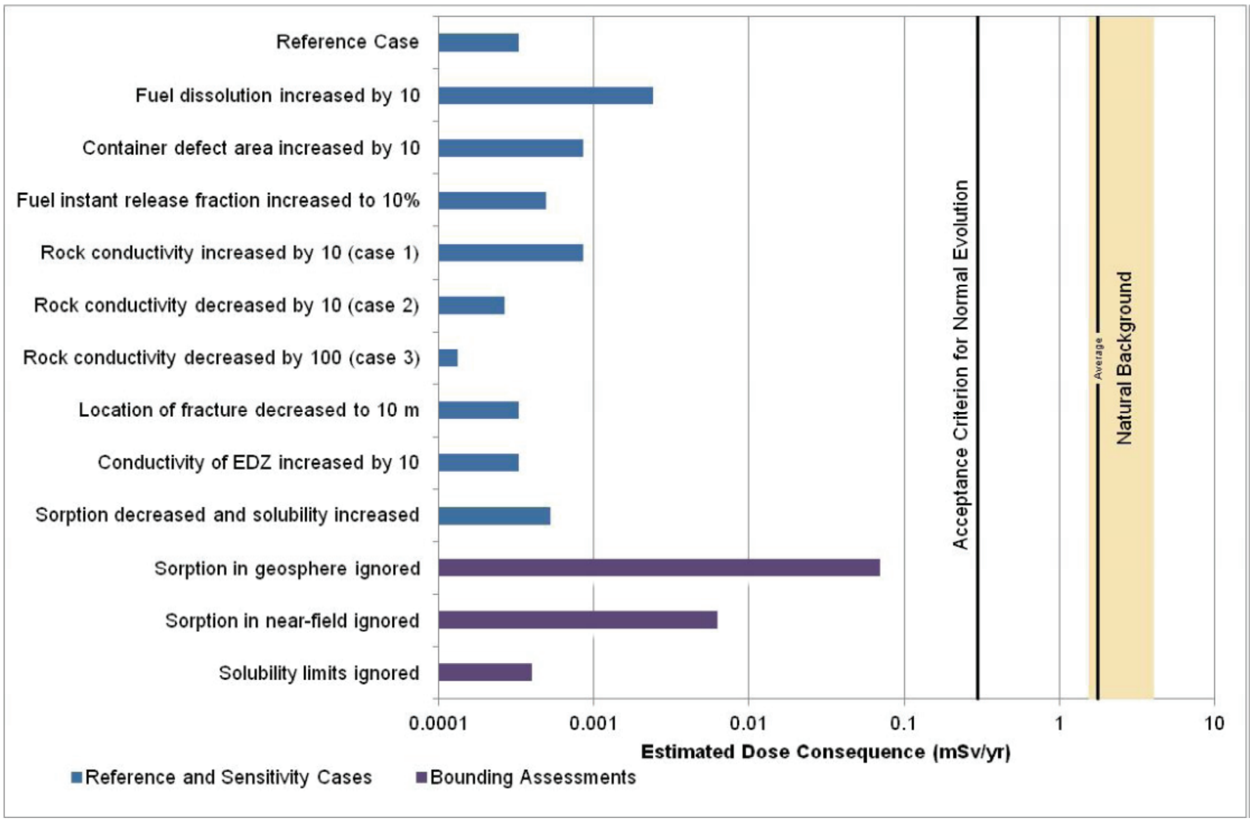

Figure E1: Results from Sensitivity Analysis and Bounding Assessments

Disruptive Scenarios

A number of disruptive or "what-if" scenarios are identified by examining possible failure mechanisms. These scenarios are assessed to evaluate the potential impact of major barrier failures on safety, in accordance with CNSC Guide G-320. The disruptive event scenarios considered in this illustrative case study include:

- Container failures at 60,000 years;
- Container failures at 10,000 years;
- Container failure at 10,000 years with varying hydraulic conductivity; and
- Failure of seals.

The container failure scenarios (i.e., all containers fail at 60,000 years and a variation where all containers fail at 10,000 years due to some unanticipated effect of glaciations such as beyond-design mechanical loading or unexpected changes in groundwater chemistry) indicate a significant increase in the peak dose results. However, the peak doses remain below the interim dose acceptance criterion of 1 mSv per year for disruptive scenarios.

The results also reveal that there is low sensitivity to peak dose to the assumed failure time of all used fuel containers in the reference case geosphere. This occurs primarily as the assumed container failure time is longer than the short-lived fission product decay time. The remaining actinides and most of the remaining long-lived fission products are sorbed within the clay-based engineered barriers and natural barrier of the enclosing rock mass so that the peak dose rate does not substantially change between these two cases.

The peak results are found to be more sensitive when varying the geosphere hydraulic conductivity at the same time as having all the containers fail at 10,000 years. When the hydraulic conductivity is increased by a factor of 10, the peak dose rate is 1.7 times above the disruptive events interim dose acceptance criterion of 1 mSv per year and it occurs at 17,000 years. This result suggests that a candidate site with a rock mass hydraulic conductivity on the order of 4 x 10-10 m/s or higher would have the potential to exceed the interim dose acceptance criterion for disruptive scenarios.

And finally, a stylized analysis was completed for inadvertent human intrusion. This scenario is a special case, as recognized in CNSC Guide G-320, since it bypasses all the multiple barriers put in place, and therefore the associated dose consequence could exceed the regulatory dose limit. The results show a potential dose to the drill crew, and to a site resident, from early intrusion, exceeds the dose limit. However, the likelihood of this event occurring is very small due to placing the used fuel containers deep underground in a location with institutional controls in place for a period of time, no economically viable mineral resources, and no potable groundwater resources. Normal deep drilling practices (e.g., control of drilling fluids, use of gamma logging, etc.) will also tend to reduce consequences relative to those estimated here. Although the likelihood of human intrusion cannot be readily defined, it will be very low. The annual risk of health effects from human intrusion is estimated to be less than 1 in 100,000 per year.

Conclusion

This report describes the reference design for a deep geological repository in crystalline rock and provides an illustrative postclosure safety assessment approach which is structured, systematic and consistent with CNSC Guide G-320. The illustrative assessment includes a description of the repository system, systematically identifies scenarios, models and methods for evaluating safety, uses different assessment strategies, addresses uncertainty, and compares the results of the assessment with interim acceptance criteria.

The postclosure safety assessment shows, for the normal evolution scenario and associated sensitivity cases, that all radiological and non-radiological interim acceptance criteria are met with substantial margins during the postclosure period. This result is consistent with previous assessments of a deep geological repository in Canada, as well as with safety assessment studies by other national radioactive waste management organizations.

ABSTRACT

Title: **Used Fuel Container Retrieval from a Deep Geological Repository in Sedimentary Rock Horizontal Tunnel Configuration**
Report No.: **NWMO TR-2012-17**
Author(s): J.E. Villagran and D. Marinceu
Company: NWMO
Date: September 2012

This report describes a conceptual design for a used fuel container retrieval system and the container retrieval operation for a deep geological repository in sedimentary rock. The conceptual design for the repository consists of a network of shafts and tunnels that provide access to several panels of placement rooms, where the used fuel containers are placed horizontally on a pedestal of highly compacted bentonite surrounded by bentonite-based backfill materials. The horizontal placement tunnels have a circular cross section and the containers are positioned coaxially with the tunnel, which results in a uniform backfill thickness between the container and the host rock.

The container retrieval system described in this report provides the means to safely retrieve a used fuel container from its location in the repository and to transfer it to the repository surface facilities. The retrieval system key components include a process for dissolution and extraction of the tunnel backfill materials and specially designed equipment to free the used fuel container and place it into a container transfer cask for transport to the surface facilities.

Safety is a key consideration for the used fuel container retrieval operation. The conceptual design of the retrieval system equipment provides the required radiation shielding for protection of personnel during all the steps of the operation. Monitoring of radiation fields and sampling of the underground environment can be conducted throughout the entire container retrieval operation.

ABSTRACT

Title: **Development of a Monitoring Program for a Deep Geological Repository for Used Nuclear Fuel**
Report No.: **NWMO TR-2012-18**
Author(s): J.E. Villagran
Company: Nuclear Waste Management Organization
Date: October 2012

This report outlines the Nuclear Waste Management Organization's (NWMO's) approach for developing a repository monitoring program within the framework of implementing Adaptive Phased Management (APM), the approach selected by the Government of Canada for the long-term management of Canada's nuclear fuel waste. The report defines the basis for the monitoring function, examines requirements and possible monitoring methods during specific phases in the life of a geological repository, and outlines a plan for the development of monitoring system designs.

The end-point of APM is placing used nuclear fuel in a deep geological repository constructed in a suitable rock formation. Monitoring used nuclear fuel in a deep geological repository is a key feature of APM. Within this context, there are two primary monitoring functions: i) confirming the long-term safety performance of the repository and, ii) providing information that may be required for future decisions.

Current deep geological repository concepts for nuclear fuel waste are based on passive safety. This derives from the premise that long-term safety can only be assured if further actions to ensure safety are not required after the end of repository operations. However, although it is expected that actions to ensure safety will not be required, it is considered important to provide the means for verifying that repository performance will be as predicted.

NWMO will continue to develop conceptual repository designs that include methods for monitoring repository performance as well as preliminary systems to assess the potential viability and effectiveness of several monitoring functions. There is a need for defining the basis and scope of a repository monitoring program within the APM work plan. This report takes the initial steps to fulfill that need and identifies a set of specific goals for the different stages of implementation of the APM project. The important elements of the monitoring work plan include:

- stating a clearly defined basis for monitoring;
- establishing a process for identifying important monitoring parameters;
- developing monitoring strategies for the potential host rock formations;
- selecting key monitoring parameters based on preliminary repository designs;
- identifying suitable technologies to monitor those parameters;
- developing preliminary monitoring system designs; and
- applying the developed processes and strategies to a site-specific repository design.

ABSTRACT

Title:	**Thermo-Mechanical Analysis of a Multi-Level Repository for Used Nuclear Fuel**
Report No.:	**NWMO TR-2012-19**
Author(s):	José L. Carvalho Charles M. Steed
Company:	Golder Associates Ltd.
Date:	September 2012

This report documents the thermo-mechanical analyses for the reference APM repository layout and addresses the optimization of the placement room spacing based on an alternate inventory of 7.2 million used CANDU fuel bundles placed in two repository levels. It also addresses the mechanical and thermally induced stress regimes and damage zones around the placement rooms and in-floor boreholes for the multi-level repository.

In addition to the impact of the containers on the in-floor boreholes and placement rooms (near field), the report addresses the thermally induced uplift at surface as well as any thermally induced distressed zone at surface (far-field) for the alternate inventory of 7.2 million used CANDU fuel bundles placed in two levels.

Through thermo-mechanical analysis of a unit cell of the repository (centreline to centreline of placement rooms, and centreline to centreline of containers), it has been established that, with the repository at depths of 400 m and 800 m with a fixed distance of 4.2 m between containers, the placement rooms can be spaced at 36 m centreline to centreline without the peak temperature of the containers exceeding 100°C. Alternatively, the placement rooms can be spaced at 32 m centreline to centreline in the upper level and 38 m centreline to centreline in the lower level without the peak temperature of the containers exceeding 100°C.

This optimised spacing of the placement rooms results in a footprint of 2 km × 1.45 km for both levels using the same spacing in both levels. Using the a different room to room spacing in each level, the footprint of the multiple level repository would be 2 km × 1.5 km for the lower level and 2 km × 1.3 km for the upper level.

Far-field analysis of the repository for the alternate inventory (7.2 million used CANDU fuel bundles) placed in two levels showed that the uplift over the centre of the repository is of the order of 40 cm and that the extent of the tensile zone is of about the same size as the footprint of the repository along the long and about double the width of the repository. The depth of the tensile zone at the time of its maximum extent (about 5000 years after placement) is of the order of 90 m.

ABSTRACT

Title: **SYVAC3-CC4 User Manual, version SCC409**
Report No.: **NWMO TR-2012-21**
Author(s): C.I. Kitson, T.W. Melnyk, L.C. Wojciechowski, T. Chshyolkova
Company: Atomic Energy of Canada Limited
Date: December 2012

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 SCC409, based on SYVAC3.12 and CC4.09.

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: **SYVAC3-CC4 Theory, version SCC409**
Report No.: **NWMO TR-2012-22**
Company: Atomic Energy of Canada Limited
Date: December 2012

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 CC4.09 of the system model.

ABSTRACT

Title: **T2GGM Version 3.1: Gas Generation and Transport Code**
Report No.: **NWMO TR-2012-23**
Authors: P. Suckling[1], J. Avis[2], N. Calder[2], P. Humphreys[3], F. King[4], R. Walsh[2]
Company: [1]Quintessa Ltd., [2]Geofirma Engineering Ltd., [3]University of Huddersfield, [4]Integrity Corrosion Consulting Ltd.
Date: November 2012

T2GGM Version 3.1 is a software package that can be used to analyze the generation and transport of gases and groundwater in a deep geologic repository. The current version is Version 3.1. It includes gas generation from low and intermediate level waste, and gas generation from the corrosion of used fuel containers under relevant conditions.

This report provides a reference manual for the T2GGM software. It includes the theory for the gas generation model, the user guide with descriptions of the software inputs and outputs, a summary of the verification that the software has undergone and software validation.

T2GGM includes the following capabilities:

- Corrosion product and hydrogen gas generation from corrosion of steels and other alloys under aerobic and anaerobic conditions;
- CO_2 and CH_4 gas generation from degradation of organic materials under aerobic and anaerobic conditions;
- H_2 gas reactions, including methanogenesis with CO_2;
- Biomass generation, decay and recycling;
- Exchange of gas and water between the repository and the surrounding geosphere; and
- Two-phase flow of water and gas within the geosphere.

Key results include the gas pressure and water saturation levels within a repository, as well as flow rates of water and gas within the geosphere. T2GGM does not include radionuclide transport and decay.

T2GGM is comprised of two coupled models: a Gas Generation Model (GGM) used to model the generation of gas within a repository due to corrosion and microbial degradation of the various materials present, and a TOUGH2 model for gas-water transport from the repository through the geosphere.

ABSTRACT

Title: **State-of-the-Science Review of the Stress Field during a Glacial Cycle and Glacially Induced Faulting**
Report No.: **NWMO TR-2012-24**
Author(s): Patrick Wu
Company: University of Calgary
Date: December 2012

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

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

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

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

ABSTRACT

Title: **Review of Paleoseismological Methods for Seismic Hazard Assessment and Their Applicability to Central and Eastern Canada**
Report No.: **NWMO TR-2012-25**
Author(s): John D. Sims, PhD
Company: John Sims & Associates
Date: December 2012

Paleoseismology is the interpretation of past seismic events largely from sedimentary deposits disturbed by or resulting from fault rupture or disturbed by ground shaking. This report presents a state-of-the science overview of the discipline of Paleoseismology, accounting for the features studied, methods of study and practices before and after the publication of J.P. McCalpin's benchmark book, "*Paleoseismology*", held as the initiation of this discipline. The applicability of these methods and practices to typical central and eastern Canadian (CEC) sedimentary and crystalline environments for the purpose of designing and siting a deep geological repository are assessed.

The report describes both proven-studied and promising paleoseismological features as well as the methods of study of these features; the strengths and limitations of each feature and method is presented. The applicability of the study of these features and the methods to study them are also discussed, in the context of both the Quaternary-geological and seismological settings of Ontario and Saskatchewan. The report provides a summary for the implementation of future paleoseismological work, considered necessary for the siting of a deep geological repository.

ABSTRACT

Title:	**Seismic Activity in the Northern Ontario Portion of the Canadian Shield - Annual Progress Report for the Period January 01 – December 31, 2011**
Report No.:	**NWMO TR-2012-26**
Author(s):	S.J. Hayek[1], J.A. Drysdale[1], J. Adams[1], V. Peci[2], S. Halchuk[1] and P. Street[1]
Company:	[1]Canadian Hazards Information Service [2]V. Peci under contract to CHIS
Date:	May 2012

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 2011.

CHIS maintains a network of sixteen 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), and Pukaskwa National Park (PNPO). 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 2011, 79 events were located. Their magnitude ranged from 0.9 m_N to 3.0 m_N. The largest events included three m_N 3.0 events: two in James Bay, and one 81 km east of Collins, ON. The most westerly events in the area being studied were two small events (m_N 2.0 and 2.1), located 113 km northeast of Gimli, MB. The 79 events located in 2011 compares with 118 events located in 2010, 82 events in 2009, 114 events in 2008, 68 events in 2007 and 83 events in 2006.