RD&D Program 2011 – NWMO's Program for Research, Development and Demonstration for Long-Term Management of Used Nuclear Fuel

NWMO TR-2011-01 **April 2011**

J. Villagran, M. Ben Belfadhel, K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, A. Khan, E. Kremer, G. Kwong, T. Lam, P. Maak, J. McKelvie, C. Medri, A. Murchison, S. Russell, M. Sanchez-Rico Castejon, U. Stahmer, E. Sykes, A. Urrutia-Bustos, A. Vorauer, T. Wanne and T. Yang

Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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ABSTRACT

Title: **RD&D Program 2011 – NWMO's Program for Research, Development and Demonstration for Long-Term Management of Used Nuclear Fuel**
Report No.: **NWMO TR-2011-01**
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Company: Nuclear Waste Management Organization
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Abstract
This report describes the state of knowledge, rationale and planned work program activities of the Nuclear Waste Management Organization's Adaptive Phased Management Technical Program over the period 2011 to 2015. It is the first of a series of reports that describe the planned work program and support the primary objective of completing preliminary designs, safety cases, cost estimates and generic research activities for a used fuel deep geological repository to support a licence application following the planned selection of a preferred site by 2018.

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

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

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

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

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

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1 INTRODUCTION

The Nuclear Waste Management Organization (NWMO) was established by the nuclear electricity generators in Canada and is responsible under the *Nuclear Fuel Waste Act* for implementing Adaptive Phased Management (APM), the Government of Canada selected approach for long-term management of used nuclear fuel (NWMO 2005, NRCan 2007). Technically, APM has as its end point the centralized containment and isolation of used nuclear fuel in a deep geological repository constructed in an appropriate host rock formation. APM is both a technical method and a management system that includes as a primary component a collaborative, phased, decision-making process (NWMO 2009).

1.1 VISION, MISSION AND VALUES

NWMO's vision is the long-term management of Canada's nuclear waste in a manner that safeguards people and respects the environment, now and in the future. Accordingly, NWMO sees as its mission to develop and implement collaboratively with Canadians a management approach for the long-term care of Canada's used nuclear fuel that is socially acceptable, technically sound, environmentally responsible and economically feasible.

NWMO will conduct the tasks for implementing its mission with openness and respect for all persons and organizations involved. NWMO will pursue the best knowledge, understanding and innovative thinking in the technical activities, engagement processes and decision-making. It will seek the participation of all communities of interest and be responsive to a diversity of views and perspectives, communicating and consulting actively, and facilitating a constructive dialogue.

NWMO will be fully responsible for the prudent and efficient management of resources and accountable for all its actions. It will be open and transparent in the process, communications and decision-making, so that the approach is clear to all Canadians.

1.2 STRATEGIC OBJECTIVES

To guide its early years of implementation of APM, the NWMO established seven strategic objectives. These strategic objectives, which have been the subject of public discussion and review since 2007, are the following:

1. Continue to build long-term relationships with interested Canadians and Aboriginal people and involve them in setting future directions for the long-term management of used nuclear fuel.

2. Implement together with Canadians a process to select a suitable site for the used fuel deep geological repository in an informed, willing community.

3. Refine and further develop the generic designs and safety cases for a used fuel deep geological repository in both crystalline and sedimentary rock formations and conduct technical research to support continuous improvements.

4. Ensure funds are available to pay for the long-term management of Canada's used nuclear fuel.

5. Advance research in areas to support the implementation of Adaptive Phased Management including technology, social values and public policy. Adapt plans in response to new knowledge and continuous improvement.

6. Maintain a governance structure that provides the Canadian public, governments and the NWMO Members, Board of Directors and management with assurance, oversight, advice and guidance about NWMO's implementation of Adaptive Phased Management.

7. Build an organization with the social, environmental, technical and financial capabilities to implement Adaptive Phased Management.

1.3 IMPLEMENTING ADAPTIVE PHASED MANAGEMENT

Used nuclear fuel remains radioactive for a long period of time and it must be contained and isolated from people and the environment for hundreds of thousands of years. Canada's used nuclear fuel is presently safely managed in licensed storage facilities at nuclear reactor sites in Ontario, Québec and New Brunswick, and at Atomic Energy of Canada Limited's (AECL) nuclear research sites in Manitoba and Ontario.

Over the past 40 years, Canada's nuclear power program has produced just over two million used fuel bundles. Each CANDU fuel bundle is approximately 10 cm in diameter and 50 cm in length, and weighs about 24 kilograms. When a fuel bundle is removed from a reactor, it is first placed in the irradiated fuel bay (IFB), a water-filled pool that provides shielding and cooling for a minimum period of seven years, during which its heat generation rate and radioactivity will significantly decrease. Following the period of storage at the power station's IFB, the used fuel bundle is placed in dry storage, typically in Dry Storage Containers (Ontario), silos (New Brunswick) or storage vaults (Québec).

APM is the Government of Canada selected approach for the long-term management of Canada's used nuclear fuel and has as its end point the placement of used nuclear fuel in a deep geological repository to safely contain it and isolate it from humans and the environment.

The NWMO has responsibility under the *Nuclear Fuel Waste Act* for implementation of APM. The nature of this task requires a unique combination of scientific knowledge and skills in technical, social and management areas. The process of selecting a site, designing the repository, and constructing and safely operating the facility requires the integrated execution of several long-term projects. Each of the activities that are part of APM, including their planning, development and implementation include extensive dialogue and consultation with Canadians, Aboriginal peoples and other interested organizations.

1.4 REGULATORY FRAMEWORK

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

In 2004, the CNSC published Regulatory Policy P-290, *Managing Radioactive Waste*. The policy states several principles that will be considered during regulatory decisions on the management of radioactive waste. For example, waste minimization, management of waste commensurate with risk, and the time period for assessment of future impacts.

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

With respect to a deep repository for used nuclear fuel, the application for a CNSC licence triggers an Environmental Assessment (EA) under the Canadian Environmental Assessment Act (CEAA), which is required to assess the environmental effects of most projects requiring federal action or decisions. Public input will be required at an appropriate stage in the EA and licensing process.

Currently, NWMO is in a pre-project phase regarding the development and licensing of a used fuel repository. An agreement between the CNSC and NWMO established in March 2009 enables CNSC staff to provide regulatory guidance to the NWMO in relation to the implementation of APM and a pre-project review of APM conceptual designs and safety assessments. In addition, NWMO maintains regular contact with CNSC staff by keeping them informed of the progress being made in the implementation of APM (NWMO 2009).

2 PURPOSE AND SCOPE

2.1 PURPOSE

The purpose of this report is to document state of knowledge, rationale and NWMO's planned technical work program activities in the areas of repository engineering, safety assessment, geosciences and transportation of used nuclear fuel to a deep geological repository (see Figure 2.1).

2.2 TECHNICAL PROGRAM OBJECTIVES

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

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

1. Prepare updated generic reference designs, cost estimates and safety cases for a deep geological repository in crystalline rock and in sedimentary rock.

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

3. Further increase confidence in the deep geological repository safety cases.

4. Obtain Canadian Nuclear Safety Commission pre-project review of reference designs and safety cases for a deep geological repository in crystalline rock and in sedimentary rock by 2013.

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

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

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

The two main work areas supporting these objectives are:

a) Deep geological repository design development and the safety case which will ensure NWMO has the appropriate level of engineering design and safety to support a future application of a site licence (objectives 1, 2 and 4); and

b) Building confidence in the safety case and improving our understanding of processes in the repository that may affect safety in the near and long term (objectives 3 and 5).

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

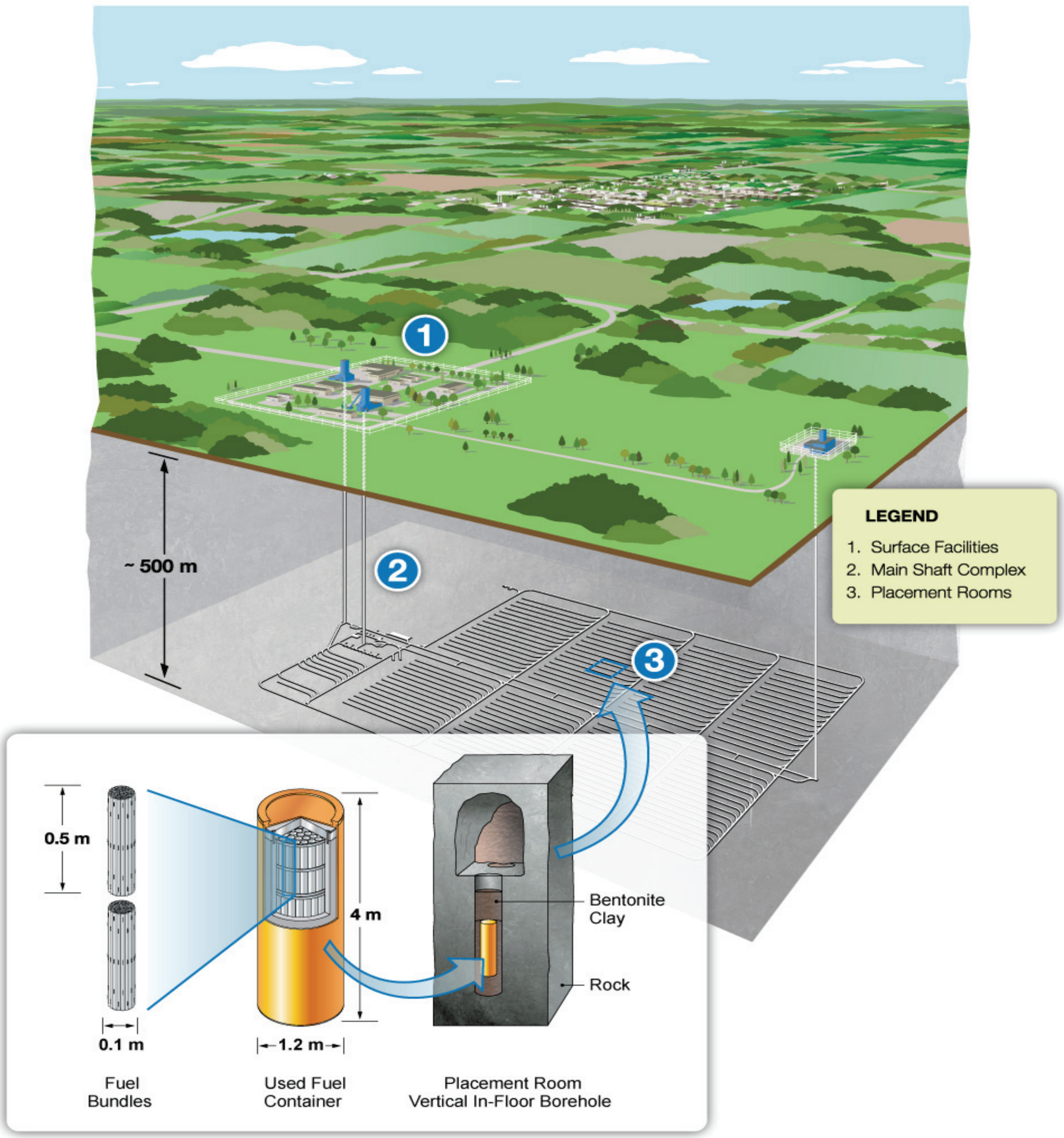

Figure 2.1: Adaptive Phased Management – Deep Geological Repository

2.3 PLANNING ASSUMPTIONS

The current planning assumptions related to near-term progress in the implementation of APM during the siting phase are as follows (see Figure 2.2):

a) Initiate APM site selection process in 2010.

b) Conduct initial screenings and desktop feasibility studies in 2011.

c) Initiate preliminary field investigations in 2012.

d) Initiate detailed underground site characterization in one or more sites in 2014.

e) Selection of preferred site in 2018.

These assumptions are used to guide the development of NWMO's Technical Program supporting implementation of APM and to identify potential funding requirements.

2.4 TECHNICAL PROGRAM FOCUS

Over the next few years, the APM Technical Program will focus on the following key areas of work:

i) Update reference engineering designs and cost estimates for a used fuel deep geological repository and used fuel transportation system;

ii) Further optimize the reference designs for a deep geological repository in crystalline rock and in sedimentary rock;

iii) Prepare illustrative postclosure safety assessments for a deep geological repository in crystalline rock and in sedimentary rock;

iv) Obtain Canadian Nuclear Safety Commission pre-project review of repository conceptual designs and safety assessments; and

v) Complete preliminary geoscientific screening, characterization and evaluation of potential sites for a used fuel repository in support of the siting process.

These key areas of work are on top of a base program of technical activities in geoscience, safety assessment, repository engineering and regulatory affairs conducted with Canadian and international partners to ensure that the best knowledge and understanding in each specific area is being applied.

The work of the APM Technical Program has been allocated to two main work areas plus two supporting activities, as follows:

- Work Program "A": Design Development and Safety Case
- Work Program "B": Confidence Building and Process Understanding
- Work Program "C": Site Characterization and Evaluation
- Work Program "D": Alternative Methods

The letter designation "A", "B", "C" or "D" has been assigned to the Work Program activities described in the following sections of this report.

		Illustrative APM Implementation Schedule	
Calendar Year	**Year**	**Major Activities and Assumptions for Financial Planning & Work Program**	
2007		Government Decision	
2008		**develop Siting Process**	
2009			
2010	Y01	Initial screening of communities Feasibility studies in potential sites Prelim field investigations	Initiate siting process; outreach activities Briefings & resources for communities Third-party reviews
2011	Y02		
2012	Y03		
2013	Y04		
2014	Y05	Surface & subsurface investigations in candidate sites Design & safety assessment work Select preferred site	Engage potentially affected communities Socio-economic impact assessments Detailed site investigations in collaboration with communities; discussion of benefits Negotiate terms & conditions for agreement
2015	Y06		
2016	Y07		
2017	Y08		
2018	Y09		
2019	Y10	Apply for Site Prep & Construction Licence Finalize site-specific design & safety assessment work for EA & licence	NWMO & community ratify formal agreement to host facility Benefits to host community
2020	Y11		
2021	Y12		
2022	Y13	EA & licensing process Obtain Site Preparation & Underground Demo Facility Licence	Establish centre of expertise (surface), in partnership with community Participant support to EA process
2023	Y14		
2024	Y15		
2025	Y16	Construct Underground Demo Facility Begin site-specific demonstrations of repository technology Final design & safety assessment Obtain Repository Construction Licence	Establish centre of expertise (underground) Community offsets & benefits Socio-economic impact monitoring
2026	Y17		
2027	Y18		
2028	Y19		
2029	Y20		
2030	Y21	Apply for Operating Licence Construct initial components of repository Obtain Operating Licence	Centre of expertise (surface / underground) Community offsets & benefits Socio-economic impact monitoring
2031	Y22		
2032	Y23		
2033	Y24		
2034	Y25		
2035	Y26	**begin APM Repository Operation (30 years)**	
…	…	…	…
…	…	…	…
2064	Y55	**end APM Repository Operation**	
2065	Y56	**begin Extended Monitoring (70 years or more)**	
…	…	…	…
…	…	…	…
…	…	…	…
…	…	…	…
2134	Y125	**end Extended Monitoring**	
2135	Y126	**begin Decommissioning & Closure (25 years)**	
…	…	…	…
…	…	…	…
2159	Y150	**end Decommissioning & Closure**	
2160	Y151	**Abandonment & begin Postclosure Monitoring**	

Figure 2.2: Adaptive Phased Management – Deep Geological Repository

3 USED NUCLEAR FUEL

3.1 FUEL INVENTORIES

3.1.1 Current Fuel Inventories

The Canadian used nuclear fuel inventories and forecasts are documented in an annual NWMO report (Garamszeghy 2010). Table 3-1 summarizes these used fuel inventories as of June 30, 2010, expressed in terms of number of CANDU fuel bundles. These numbers exclude the fuel resident in the reactors at that date as well as non-standard experimental fuels currently in storage at AECL's Chalk River Laboratories.

Table 3.1: Used Nuclear Fuel Inventories in Canada as of June 30, 2010

Location	Waste Owner	Wet Storage (# bundles)	Dry Storage (# bundles)	TOTAL (# bundles)
Bruce A	OPG	364,381	46,464	410,485
Bruce B	OPG	375,566	145,912	521,478
Darlington	OPG	329,198	48,363	377,561
Douglas Point	AECL	0	22,256	22,256
Gentilly 1	AECL	0	3,213	3,213
Gentilly 2	HQ	29,833	86,340	116,173
Pickering A	OPG	401,737	214,436	616,173
Pickering B	OPG			
Point Lepreau	NBPN	40,758	81,000	121,758
AECL Whiteshell	AECL	0	2,268	2,268
AECL Chalk River	AECL	0	4,886	4,886
	TOTAL	**1,541,473**	**655,138**	**2,196,611**

Notes: 1) AECL = Atomic Energy of Canada Limited; HQ = Hydro-Québec
NBPN = New Brunswick Power Nuclear; OPG = Ontario Power Generation Inc.
2) 360 bundles of Whiteshell fuel are standard CANDU bundles. The remaining bundles are various research fuels, similar in size and shape to standard CANDU bundles

In addition to the quantities shown in Table 3-1, AECL also has ~22,000 items of research reactor fuel and experimental fuels in storage at the Chalk River Laboratories.

3.1.2 Reference Fuel Inventories

Forecasts of future nuclear fuel waste arisings from existing reactors are based on scenarios constructed for NWMO planning purposes only, and provide a range of possible fuel arisings. For the purpose of current technical RD&D work, only two fuel inventories are considered, both expressed in millions of CANDU used fuel bundles. These inventories encompass the possible nuclear power development scenarios envisaged at this time and consist respectively of a reference inventory of 3.6 million and an upper bound inventory of 7.2 million of CANDU used fuel bundles.

3.2 PROCESSES IN THE FUEL

The radioactivity, heat output, composition and physical structure of used fuel are affected by the number of fission reactions that have taken place within the fuel during its residence time in the reactor. This is roughly proportional to the fuel burnup, which is the energy released per unit mass of uranium. The typical burnup of CANDU fuel ranges from 120 to 320 MWh/kg U, with a mean burnup value from 200 to 220 MWh/kg U. At this burnup level, approximately 2% of the initial uranium has undergone fission and converted into other elements (Tait et al, 2000).

3.2.1 Radioactive Decay and Heat Generation

When used fuel is first removed from the reactor it is highly radioactive, but its activity rapidly decreases, as shown in Figure 3.1. During the first year the radioactivity decreases to about 1% of its initial value, and within 10 years it decreases to about 0.01% of its initial value. During the first 500 years radioactive decay is dominated by fission products, most of which are gamma emitters. Thereafter, the decay process is dominated by actinides, including uranium, which decay mainly by the emission of alpha particles. After about a million years, the radioactivity in the fuel will have declined to a level close to that of its natural uranium content.

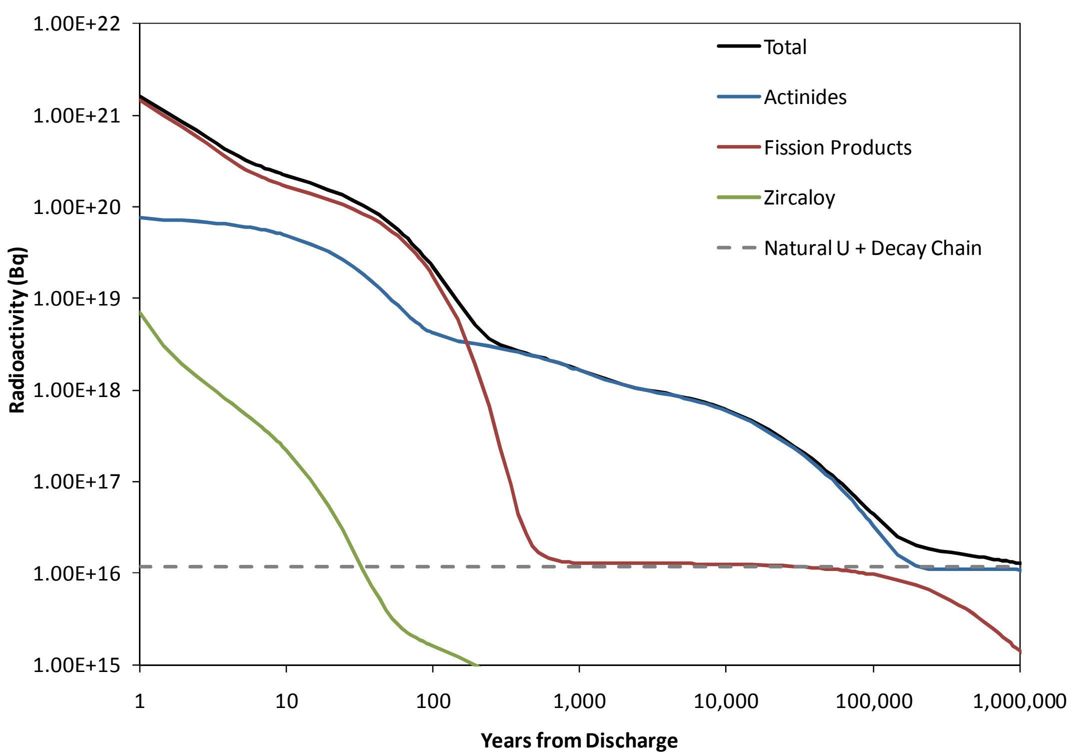

Figure 3.1: Activity of used CANDU fuel with a burnup of 220 MWh/kgU for times up to 1 million years.

The radionuclide inventory, radiation output, and heat output of used fuel as a function of time and burnup have been calculated using the ORIGEN-S code (Tait and Hanna 2001). The change in inventory for key radionuclides over the first million years is shown in Figure 3.2. The inventories of most radionuclides decrease with time due to radioactive decay, although the inventories of some radionuclides produced by radioactive decay (e.g. Np-237, U-235 and Ra-226) will increase with time. Ultimately, the decay of radioactive elements produces stable elements such as Pb and He.

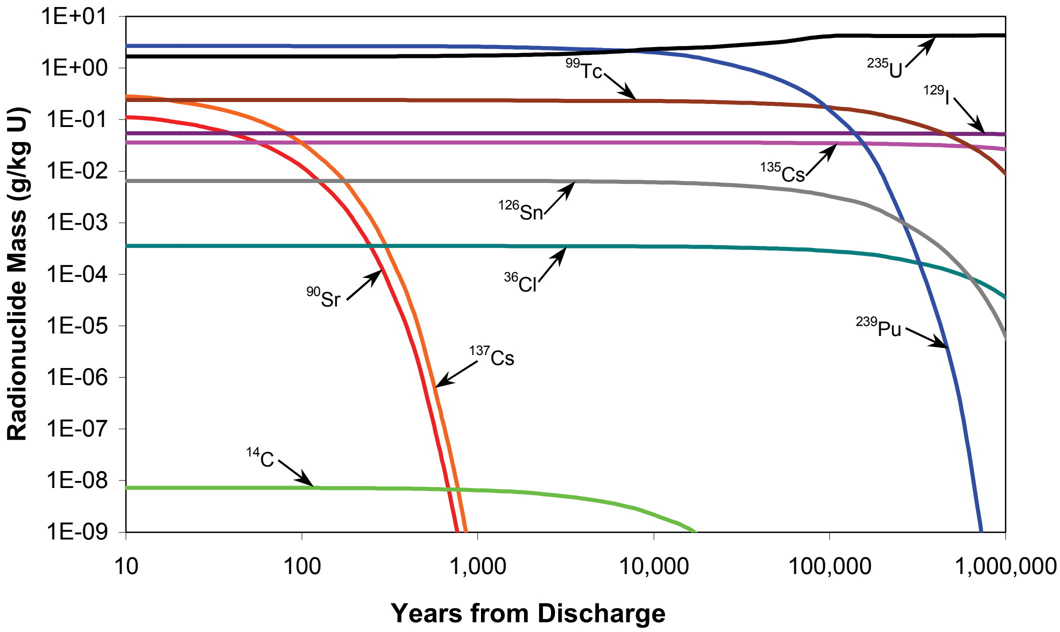

Figure 3.2: Change in inventory of some key long-lived radionuclides over time in used fuel (220 MWh/kg U burnup). ^{238}U (not shown), the most abundant radionuclide in the used fuel, is present at 982 g/kg U. The inventory of ^{235}U increases as it is produced from the decay of ^{239}Pu.

Much of the energy carried by the alpha, beta and gamma radiation is absorbed in the fuel itself, causing it to heat up. Immediately after being removed from a power reactor, a CANDU used-fuel bundle with average burnup up produces about 27,000 watts of heat. After 100 years the same bundle would produce only about 3 watts of heat. Figure 3.3 shows the decrease in thermal power output as a function of time for a used fuel container that holds 324 fuel bundles with an average burnup of 220 MWh/kg U. The plot shows that within 100 years after being placed in a repository the fuel container heat output will be less than 500 watts. After 500 years the heat fuel container output will be approximately equal to that of two 60-watt light bulbs.

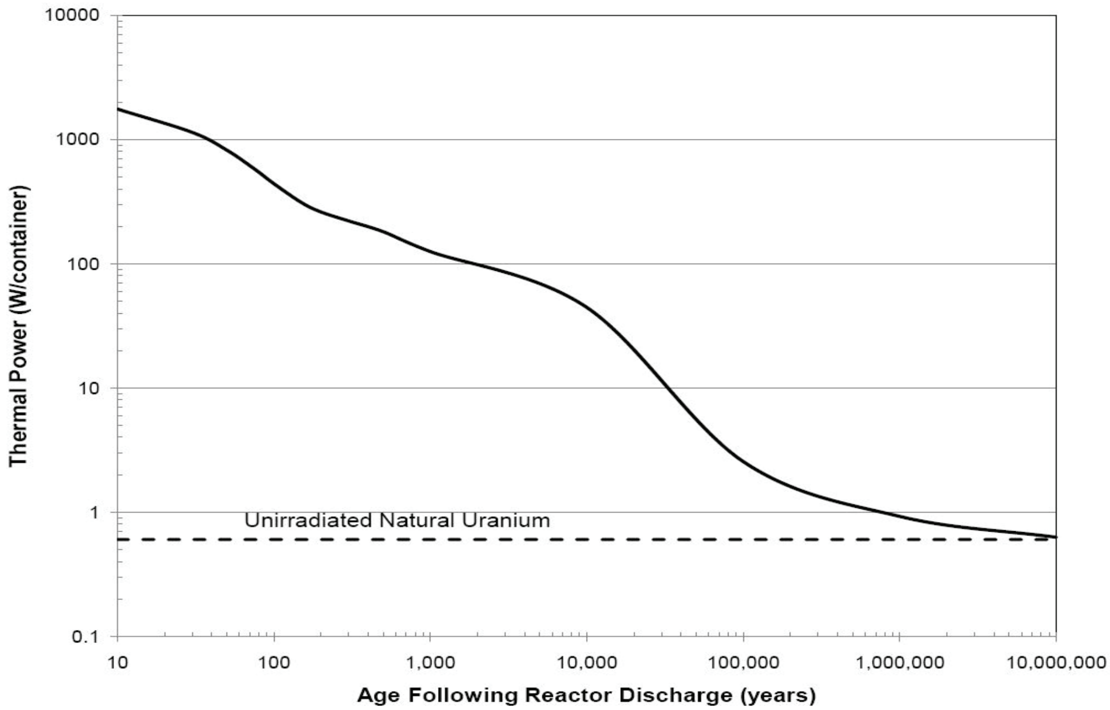

Figure 3.3: Decrease in the thermal power of a 324 bundles container as a function of time for 220 MWh/kg U burnup fuel. Within 100 years, the container heat output would be less than 500 watts.

3.2.2 Radionuclide Distribution in Used CANDU Fuel

CANDU UO_2 fuel is fabricated with natural uranium. Non-irradiated UO_2 fuel has a cohesive, microstructure and grains have internal sintering porosity from the fuel fabrication process. In the reactor, the UO_2 fuel undergoes a number of microstructural changes as illustrated in Figure 3.4. The sintering porosity is largely eliminated, grain boundaries become more distinct and volatile elements diffuse out of the fuel grains (Novak and Hastings 1991, Johnson and Shoesmith 1988). At the average burnup the used fuel discharged from a CANDU reactor is more than 98% UO_2. About 2% of the fuel mass has been replaced by elements that include:

- fission products generated by the fission of U-235 and Pu-239 in the fuel,
- activation products, generated by neutron capture reactions, and
- actinides other than uranium (e.g., neptunium, plutonium), generated by successive neutron capture or radioactive decay.

More than 95% of the nuclides that are produced in the reactor remain within the UO_2 grains, very close to the location of their formation (Johnson and Shoesmith 1988). As illustrated in Figure 3.4 the elements produced by nuclear fission can be classified into three major groups according to their chemical behaviour (Johnson et al. 1994):

- Elements such as Xe, Kr, Cs, and I, gaseous or semi-volatile at reactor fuel operating temperatures. While the fuel is in the reactor, a few % of these elements migrate from the UO_2 grains to the grain boundary, forming gas bubbles, and some of these further move into the fuel element void spaces (Johnson et al. 2005, Johnson et al. 2004). For the purpose of safety assessment calculations, the fraction of these elements that migrates out of the fuel grains is considered to be available for instantaneous release if the fuel sheath is damaged, and it is defined as the Instant Release Fraction (IRF).

- Elements such as Mo, Ru and Pd that are non-volatile and have a low solubility in UO_2. At reactor temperatures, small quantities of these elements diffuse out of the UO_2 grains and segregate as metallic alloy phases at grain boundaries (Novak and Hastings 1991). The majority of these elements, however, have low diffusion coefficients and remain trapped within the fuel grains.

- Lanthanide and actinide elements (e.g., Eu, Pu, and Np) are compatible with the UO_2 crystalline structure and remain in the lattice, within the UO_2 grains.

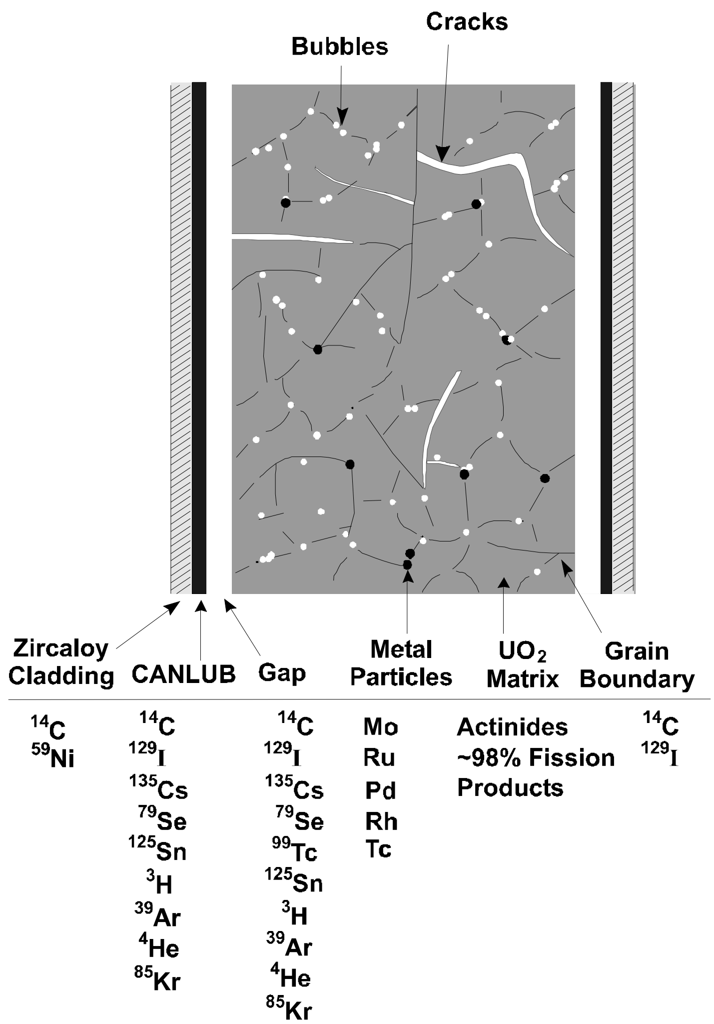

Figure 3.4: Distribution of some fission products and actinides within a used fuel element (not to scale), after Johnson et al. 1994.

The quantity of fission gases in the fuel-sheath gap is measured by puncturing used fuel elements. Recent NWMO work shows that measured fission gas release from CANDU fuel correlates with the peak linear power rating (LPR), not with fuel burnup. Figure 3.5 shows that fission gas releases from typical CANDU fuel bundles are < 1% for peak LPR values less than 44 kW/m, but increase sharply above that value. Consequently, the average instant release fractions for CANDU fuels are expected to depend on the distribution of LPRs, while the total radionuclide inventory depends on the fuel burnup.

In order to provide better values for radionuclide inventories and IRFs, the burnup and LPR distributions for fuel discharged from the Bruce, Pickering and Darlington nuclear stations were determined for several time intervals covering a period from 1970 to 2006 (Wilk and Cantello 2006). The median and 90th percentile bundle peak LPR for all reactors were found to be less than 38 kW/m and 45 kW/m, respectively.

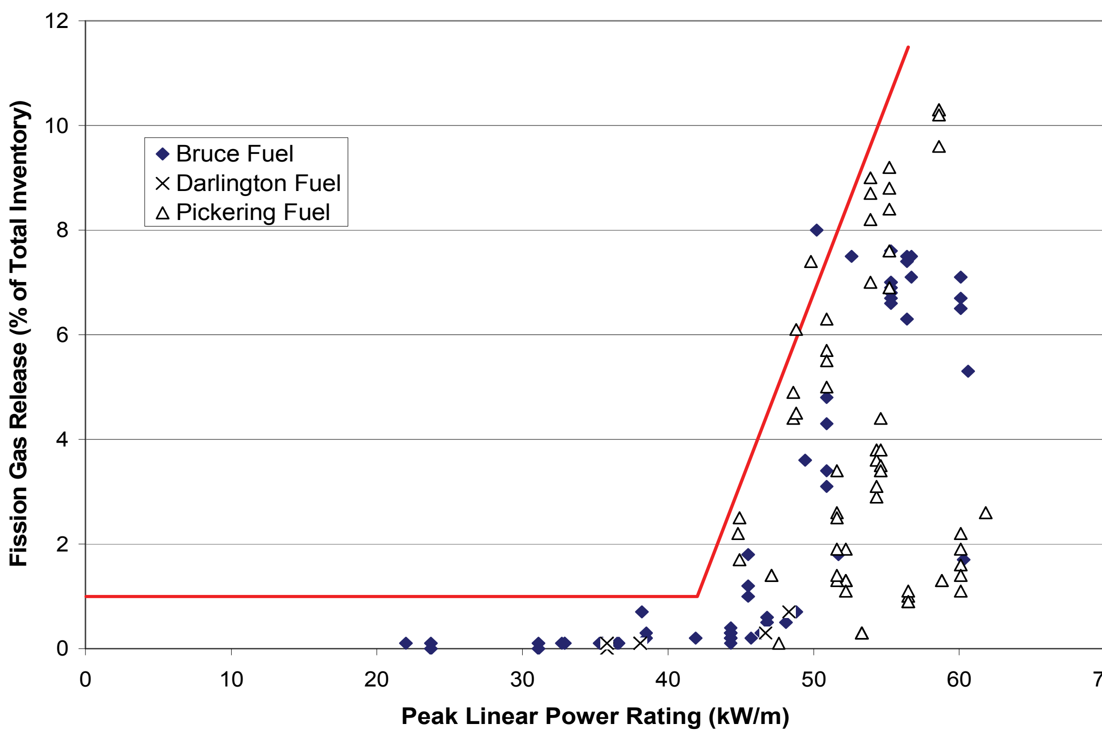

Figure 3.5: Fission gas release as a function of the fuel peak LPR for CANDU fuels with burnups < 330 MWh/kg U.

Work Program

B

The current level of knowledge of radionuclide inventory is sufficient for the present fleet of Canadian reactors with unenriched CANDU fuel. However, an updated assessment of radionuclide inventory will be needed taking into account Ontario reactor operations since 2000 and the characteristics of the other Canadian used fuel, advanced reactor fuel and/or research fuels, as required.

3.2.3 Changes in Used Fuel with Time

3.2.3.1 Build-up of Helium Gas

Alpha decay results in the formation of helium atoms in the used fuel. Since this helium is physically stable (non-radioactive) and chemically inert, the total amount of helium gas in the fuel elements increases over time. After 30,000 years the amount of helium produced by alpha decay would be approximately equal to that of the fission gases. In an undamaged fuel element it is unlikely that the rupture strength of the cladding would be exceeded in less than a million years. If a failure occurred, helium and fission gases would merely be released into the container inner volume and the fuel pellets would be exposed to the inert gas atmosphere inside the container.

Helium build-up in the fuel could also possibly lead to increased fuel cracking, i.e., separation of the fuel grains. However, recent international work has suggested that the quantity of alpha-decay produced helium in LWR UO_2 spent fuels is not sufficient to induce micro-cracking of grains in the central and intermediate parts of the pellet even at the highest burnups (Ferry et al. 2008). Natural analogue evidence also suggests that alpha irradiation damage would not cause used fuel to crumble from accumulation of gases, even after very long times (Janeczek 1999, Jensen and Ewing 2001). Hence, the microstructure of used fuel should not significantly evolve with He accumulation.

Work Program **B**

The level of knowledge on this subject is sufficient for the safety assessment of standard (non-enriched) CANDU fuel. No further work is recommended at this time.

3.2.3.2 Radiation Damage

State of Knowledge

During radioactive decay, the crystalline matrix of the used fuel experiences localized damage from the emission of alpha particles, which travel only short distances but have high linear energy transfer (LET). Various researchers (e.g., Poinssot et al. 2005, 2006, Ferry et al. 2004, Lovera et al. 2003) have discussed the possibility that, over time, alpha-radiation damage in the used fuel would increase the rate at which volatile species move from within the UO_2 fuel grains to the grain boundaries. This process is called athermal diffusion. For high burnup LWR fuels (> 45 GWd/t U, or 1080 MWh/kgU), Poinssot et al. (2006) predicted that by this mechanism 5% of the radionuclide inventory in fuel could be transported to the grain boundaries after 10,000 years, and that up to 7% could be transported after 100,000 years. However, more recent work (Ferry et al. 2008 and references therein) indicates that the enhanced diffusion for fission product atoms under alpha self-irradiation in LWR fuels is about three orders of magnitude lower than the previous upper estimate. With this new value, the contribution of alpha self-irradiation enhanced diffusion to the IRF of fission products becomes negligible.

Due to the uncertainties concerning the behaviour of activation products such as Cl-36 and C-14, however, the contribution of athermal diffusion to the IRF of activation products may need to be considered (Ferry et al. 2008).

Rationale for Future Work

CANDU fuels have much lower burnup values than LWR fuels, consequently, its alpha radiation field strengths are also much lower and the self-irradiation effects are expected to be much smaller than for LWR fuels. Therefore, athermal diffusion would not cause an increase in grain boundary radionuclide inventories and, hence, IRFs over the time frames of interest. However, athermal diffusion could influence the IRF of activation products (Ferry et al. 2008).

Work Program **B**

Theoretical work will be conducted to quantify the effects of alpha radiation damage on the IRFs of activation products such as Cl-36 and C-14.

3.2.3.3 Chemical Changes

UO_2 is a stable ceramic-like material under reducing conditions. Natural uranium ore bodies are often UO_2 (uraninite). The used fuel is expected to remain stable over 1 million years, if it is not exposed to oxygen or aerobic conditions. The chemical changes to the fuel that may have an impact on repository safety are discussed in Section 3.2.4.

3.2.4 Radionuclide Releases from the Fuel

After a container fails, water will enter the container and contact the used fuel bundles, thereby providing a pathway for release of radionuclides from the fuel to the exterior of the container. Water will contact the UO_2 fuel only after the Zircaloy cladding fails.

Studies of the interaction between used fuel and groundwater done over the last 30 years have established that radionuclide releases from the used fuel would occur via two primary mechanisms acting on different time scales. These mechanisms are called: instant release, and congruent release. The former involves the relatively rapid release of a small percentage of the inventory of a selected group of radionuclides, such as isotopes of Cs, I and Xe that reside in the fuel-sheath gap and at the fuel grain boundaries. These nuclides would be quickly accessed by water once the fuel sheath fails (Johnson et al 2005, 2004; Werme et al 2004, Garisto et al 2004). The quantity of each radionuclide that is available for “quick” release is called the instant release fraction (IRF) (Garisto et al 1989).

The second and much slower process is the congruent release of the radionuclides from the UO_2 fuel matrix, as the fuel grains themselves corrode or dissolve (Johnson et al. 1994). These two modes of release are modelled differently and are described below in further detail.

3.2.4.1 Zircaloy Corrosion

State of Knowledge

In CANDU fuel the UO_2 fuel pellets are contained in a sheath of corrosion-resistant Zircaloy typically 0.2 mm thick. However, even under the high temperatures and extreme conditions in a nuclear reactor, only a very small percentage of fuel cladding fails during operation. These failures, typically a small defect or a pinhole, occur in approximately 0.1% of the fuel bundles.

Under anaerobic repository conditions, the Zircaloy corrosion will be very slow. Recent work has estimated corrosion rates of 5 nm/yr (Shoesmith and Zagidulin, 2010). At this rate, the cladding would have a 40,000 year lifetime. However, since the cladding is very thin and since even a small hole would allow water to contact the used fuel, the cladding is not generally credited as a barrier in safety assessments. No work is currently planned on Zircaloy corrosion.

3.2.4.2 Instant Release Fraction

State of Knowledge

The IRF is an important parameter in the safety assessment of a deep geological repository (Garisto et al, 2005). Considering the time frame for a repository safety assessment, assuming that these inventories are instantly available for release at the time the water penetrates the container is a reasonable, conservative assumption. And since the rate of fuel dissolution is expected to be extremely slow, the IRF is the major contributor to the impact in terms of radiological dose.

Both the gap and grain boundary radionuclide inventories are included the IRF (Johnson et al. 2005, 2004; Garisto et al. 2004, Garisto 2002; Johnson and Tait 1997).

Rationale for Future Work

In 2008, a review was conducted of the NWMO database of instant release fractions for used CANDU fuel. The review concluded that the existing database was appropriate for present purposes, but the following options for improvement were recommended:

1. The IRFs for Cs and I should be updated to those measured by Stroes-Gascoyne (1996) and, since the IRFs for some other elements (e.g., Se) are set equal to those of I or Cs, those should also be updated.

2. IRF values should be recalculated on the basis of the LPR of the existing used CANDU fuel in storage. Experimental data indicates that IRFs are low if the fuel LPR is less than 42 kW/m, which is the case for most of the used fuel bundles currently in storage.

3. The gap and grain boundary inventories predictions made with CANDU reactor safety codes such as ELESIM should be examined to determine if they can provide useful information for predicting IRFs for fuels with different LPRs and burnups.

Work Program **B**

During 2010 the IRF database was updated based on the above recommendations. The new IRF database will be used in the Fourth Case Study for postclosure safety assessment of a deep geological repository (see Section 8.3).

Work will be initiated to determine if codes such as the CANDU reactor safety code ELESIM could provide reliable data or information for better understanding and predicting the IRF of important radionuclides for fuels with different LPRs.

As the IRFs are important parameters for safety assessment, while no major experimental program would be initiated, opportunities to improve the current data would be monitored.

3.2.4.3 Congruent Release

State of Knowledge

After the used container fails and the fuel is exposed to water, the release of radionuclides embedded in the fuel will be controlled by the dissolution rate the UO_2 fuel matrix. This process is expected to be very slow, being controlled by two mechanisms: an electrochemical process and a chemical process (Shoesmith et al. 2005, Johnson et al. 1996). Since conditions in the repository are expected to be anoxic, electrochemical dissolution of the UO_2 fuel would be driven by the oxidizing species (primarily H_2O_2) produced by radiolysis of the water in contact with the fuel pellets (Werme et al. 2004). A mechanistic understanding of the radiolytic corrosion of UO_2 is therefore important for long-term predictions of used fuel stability.

At the fuel-water interface, the dose rate from alpha emissions is the main contributor to radiolysis, producing molecular oxidants such as O_2 and H_2O_2. Electrochemical corrosion occurs when the redox conditions at the fuel surface are oxidizing and fuel oxidation has proceeded beyond a stoichiometry of $UO_{2.33}$ (Shoesmith et al. 2005, Shoesmith and Sunder 1991). The dissolution reaction under these conditions is a coupled process involving the oxidative dissolution of the UO_2 and the reduction of the available oxidant, as depicted in the equations below:

$$UO_2 \rightarrow UO_2^{2+} + 2e$$

$$\text{Oxidant} + 2e^- \rightarrow \text{Reductant}$$

Depending on the relative kinetics of these two reactions, the fuel surface will adopt a potential (corrosion potential, E_{corr}) with a value between the electrochemical equilibrium values for the two half-reactions. With both reactions away from equilibrium, fuel dissolution will proceed and the surface is said to be undergoing corrosion. The onset of UO_2 oxidation occurs when E_{corr} reaches a value of ~400 mV (vs. SCE). Below this value, fuel dissolution and, hence, mobilization of radionuclides can occur only by chemical dissolution of the fuel, which in slightly alkaline groundwaters is extremely slow. In this case, the chemical dissolution of UO_2 fuel would lead to the formation of uranium hydrides:

$$UO_2 + 2H_2O \rightarrow U(OH)_4$$

In the defective container, it is expected that the chemical dissolution process would be solubility-limited (Johnson et al. 1994, Shoesmith 2007) and, consequently, the fuel dissolution rate would depend on the rate of transport of dissolved uranium away from the fuel surface. Assuming that the fuel surface is in contact with water, for CANDU fuel, the transition from the corrosion process to chemical dissolution is expected to occur for radioactivity decay times of about 20,000 years.

Work Program B

Within the last several years, dissolved hydrogen gas (H_2) has been identified as an important factor in controlling used fuel dissolution. H_2 is generated by water radiolysis but much larger amounts are produced as a result of the corrosion of the used fuel container inner steel vessel. A review of the effects of dissolved hydrogen on the corrosion/dissolution of used nuclear fuel was published in 2008 (Shoesmith 2008). Experimental results from recent years indicate that even small quantities of H_2 can effectively suppress fuel corrosion and radionuclide releases from used fuel. Further research is planned to establish the detailed mechanisms involved in the observed phenomena and the potential impacts of H_2 on fuel dissolution.

Current Experimental Program

The NWMO-funded experimental program on fuel dissolution is conducted at the University of Western Ontario (UWO). Typically, corrosion potential (E_{corr}) measurements on UO_2 and SIMFUEL electrodes and surface analysis techniques are used in the investigations (Santos 2005, Santos et al 2006, Goldik 2005). (SIMFUEL is made by doping unirradiated natural UO_2 pellets with non-radioactive elements to replicate the chemical composition of used fuel, including formation of so-called ε-particles – alloys of the fission products Mo, Ru, Tc, Pd and Rh.) The scope of the experimental program includes:

- the influence of H_2,
- the mechanism of the H_2O_2 reaction with UO_2,
- the influence of temperature,
- the influence of fuel composition on the reactivity of UO_2, and
- the effect of pH.

Experiments have shown that dissolved H_2 could shift E_{corr} values well below the oxidation threshold of -400 mV (Broczkowski et al. 2007a, 2006, 2005; Shoesmith 2008). These experiments have also indicated that noble-metal particles (ε-particles) in SIMFUEL have significant effect on the corrosion potential in the presence of hydrogen, and that suppression of fuel dissolution could be achieved with sub-millimolar concentrations of H_2 (Carbol et al. 2005; Rollin et al. 2001). Recent experimental work at the UWO has explored the impact of hydrogen of the reaction of H_2O_2 with UO_2.

H_2O_2 is produced by the alpha-radiolysis of water, and UO_2 is oxidized by the reaction of H_2O_2 on both the UO_2 surface and the noble metal particles via the formation of OH• surface radicals. The OH• radicals formed on the noble metal particles can be scavenged by reaction with dissolved H_2 leading to a suppression of UO_2 oxidation. Since H_2 concentrations are many orders of magnitude greater than H_2O_2 concentrations, the rate of production of surface H• radicals on the noble metal particles is considerably larger than the rate for OH• formation, slowing down the UO_2 oxidation process. A $[H_2]/[H_2O_2]$ ratio of $\geq 10^6$ is sufficient to completely protect the UO_2 surface from oxidation.

Scanning electrochemical microscopy (SECM) has recently been used to determine the corrosion kinetics of UO_2 fuels with well characterized stoichiometries (He et al. 2009; 2008). The relative reactivity at different sites on the fuel surface can be determined from analysis of the SECM data (see Figure 3.6), and SECM experiments have indicated that the anodic reactivity of the fuel increases markedly with the degree of non-stoichiometry (He et al. 2009). Comparison of the SECM rate constants to the intensity of the Raman peak at 450 cm^{-1} (O-U stretch) has indicated that reactivity increases as the cubic symmetry of the fuel crystal lattice is lost due to increasing non-stoichiometry.

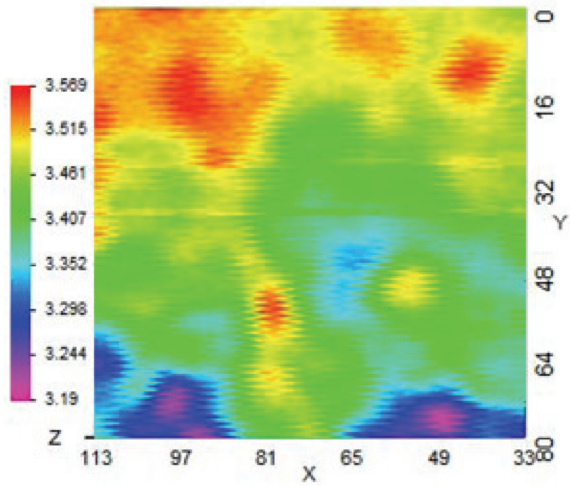

Figure 3.6: SECM map of a $UO_{2.05}$ fuel sample. The colour scale indicates the relative anodic reactivity at the fuel sites: reactive (red) to non-reactive (mauve).

Model calculations carried out in 2007 indicated that the development of local acidic sites on the UO_2 surface is possible with strongly oxidizing conditions and deep sites (i.e., pores or cracks). Furthermore, identification of studtite in natural uranium deposits suggested that acidified peroxide locations can be formed. Consequently, studies of the reaction of H_2O_2 with UO_2 fuel were extended over a wider pH range. Experiments were conducted in 2008 to determine if the mechanism and rates of anodic dissolution are the same at pH 8 and pH 9.5. Results showed no significant difference. Consequently, it is not expected that a change in pH from 9.5 to 8 would significantly affect the kinetics of the corrosion reactions on the fuel surface.

The effect of temperature on the development of local acidic conditions was also examined. Electrochemical experiments showed that the oxidation/dissolution behaviour observed at 60°C was generally similar to that observed at 22°C, although it involved substantially larger currents, i.e., an increase in temperature accelerates the rate of fuel dissolution (Broczkowski et al. 2007b). These experiments, coupled with XPS analyses, showed the following:

a) the threshold potential (-400 mV) for the onset of oxidation is similar at both temperatures;

b) the formation of U(VI) on the fuel surface occurs at lower potentials at higher temperatures, indicating an acceleration of dissolution with temperature; and

c) the development of acidity in localized sites in the fuel surface occurs at a lower potential at the higher temperature.

While features (b) and (c) suggest an increase in temperature will accelerate fuel dissolution, the indifference of the threshold potential to temperature means that the influence of H_2 on fuel corrosion will be just as effective at 60°C as at 25°C. This is consistent with previous observations which show that at 60°C a slight pressure of H_2 can reduce the corrosion potential to values below the threshold. Work is continuing to quantify the influence of temperature on fuel corrosion rates.

Rationale for Future Work

The UO_2 fuel grains in used CANDU fuel contain in excess of 95% of the total radionuclide inventory in fuel. These radionuclides are only released as the fuel dissolves. After the used fuel container fails and water contacts the fuel, the rate of fuel dissolution controls the rate of release of radionuclides from the fuel matrix. The rate of release of radionuclides from the fuel matrix is therefore an important parameter in determining the impact of the repository (Garisto et al. 2005), and it is important to fully understand the processes affecting the rate of fuel dissolution under repository conditions so that reliable predictions of the rate of fuel dissolution at long times can be made. This has been the rationale for the program studying the dissolution of UO_2 and SIMFUEL under various conditions and it is the reason for continuing the work.

Over the past decade, many of the key reactions and processes that determine the mechanism and rate of the fuel corrosion/dissolution process inside a failed waste container have been identified. While many of the details of these degradation processes are now understood, some areas remain either incompletely defined or not quantified.

Work Program **B**

The primary goals of the used fuel dissolution program will be the following:

- Continue to improve our scientific understanding of the processes controlling used fuel dissolution, in order to support the safety case;
- Extend the work to include development of an integrated comprehension of fuel and container performance;
- Extend the work to include long-term studies.

The work will be concentrated in four areas: (i) evolution of the chemical reactivity of the fuel surface; (ii) effect of H_2 on fuel corrosion and how it is influenced by the chemical evolution of surface properties; (iii) design and possible implementation of long-term exposure tests to validate model predictions; (iv) re-evaluation of laboratory-determined mechanisms and model predictions by comparison to information from the study of natural geologic analogues.

3.3 PROCESSES IN THE CONTAINER

3.3.1 Radiation Dose Rates and Radiolysis

State of Knowledge

The rate of dissolution of the used fuel depends on the alpha, beta and gamma dose rates near the fuel surface (Garisto et al. 2004). These have been calculated based on CANDU fuel radionuclide inventories (Tait et al. 2000) and specific radionuclide properties. The alpha and beta radiation dose rates to water can be calculated based on the dose rates to the uranium matrix (Sunder 1995, 1998). Gamma dose calculations were carried out using the Monte Carlo N-Particle (MCNP) software, Version 5.1.3 (Garisto et al. 2009). The alpha, beta and gamma dose rates to water in a water-filled used fuel container are shown in Figure 3.7. The calculated cumulative amount of used fuel dissolved, based on these dose rates are shown in Figure 3.8. The fuel dissolves very slowly and only 1/3 of the fuel is (conservatively) expected to have dissolved in ten million years.

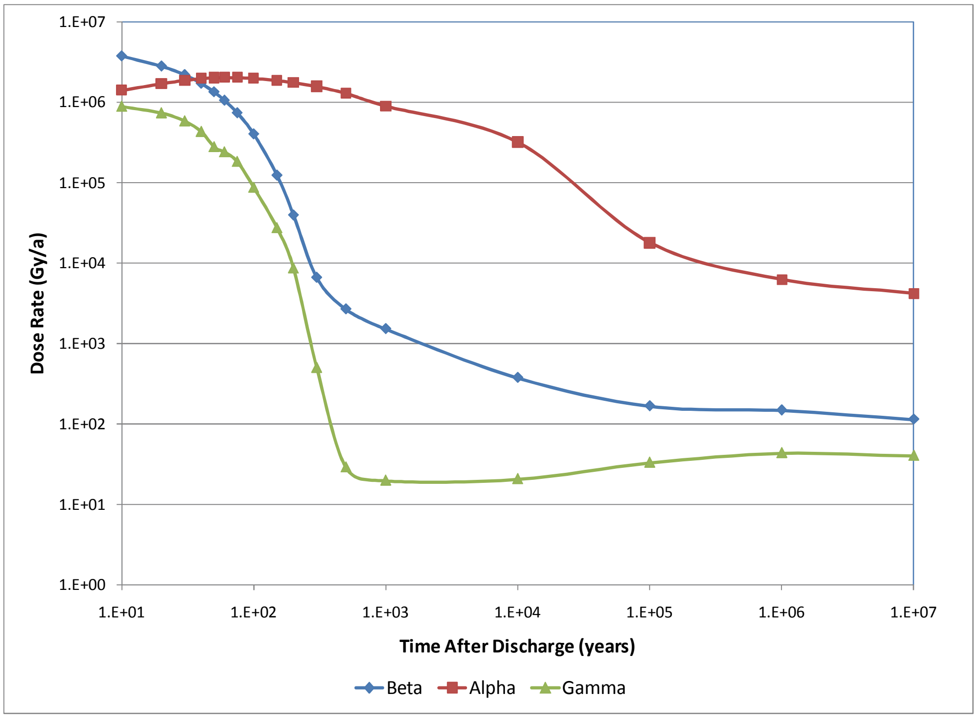

Figure 3.7: Alpha, beta and gamma dose rates to water near a used fuel bundle with a burnup of 220 MWh/kgU as a function of fuel discharge time.

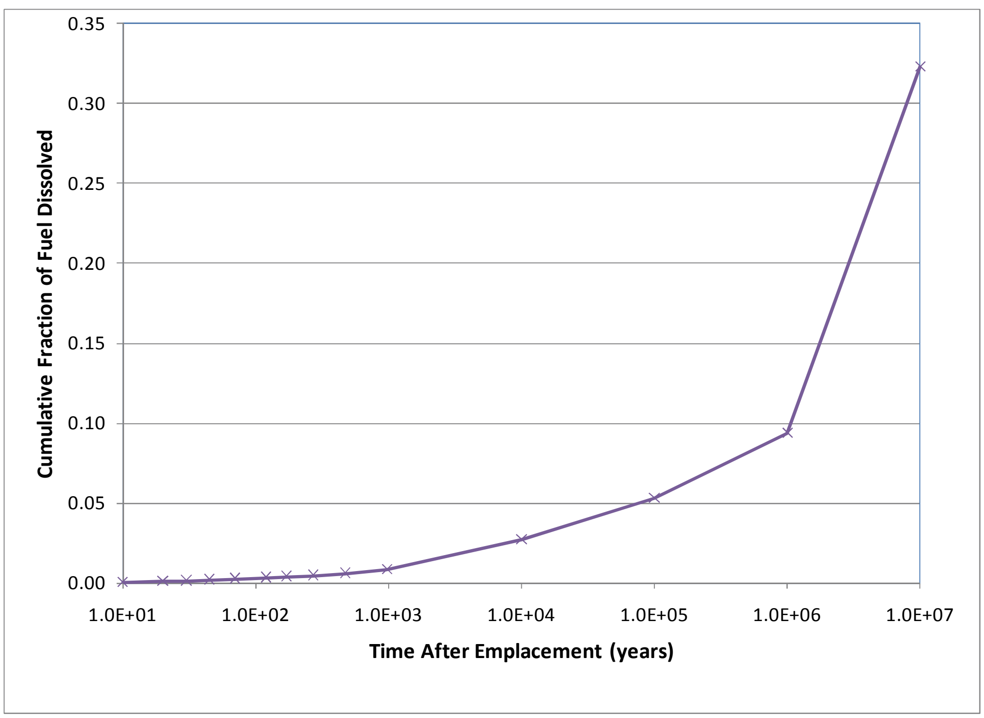

Figure 3.8: Cumulative fraction of fuel dissolved based on the used fuel dissolution model described in Garisto et al. (2004) and the radiation dose rates in Figure 3.7.

Work Program

The state of knowledge of radiation dose processes in the used fuel container is considered sufficient to conduct the safety assessment case studies planned for the next five years, involving standard CANDU fuels. Therefore, no additional research is planned in this area.

3.3.2 Solubility

Rationale for Future Work

Solubility may control the maximum concentration of important radionuclides within or near the container. In order to determine the solubility limits, thermodynamic data are required under relevant conditions. These data are normally archived in quality-controlled thermodynamic datasets. Presently, NWMO does not have a reference dataset suitable for the expected Canadian conditions. The highly saline conditions in limestone and shale sedimentary rock sites in particular are unique to Canada. Currently NWMO is evaluating a US Yucca Mountain Project Pitzer dataset for suitability, since it was designed for highly saline systems. However, this dataset has known limitations since it was not developed for relevant Canadian conditions, and also is not presently being maintained by the US.

Work Program **B**

The solubility work program will address the following activities:

- Continue to participate in the NEA Thermodynamics Database project.
- Update estimates for key radionuclide solubilities under crystalline and sedimentary rock conditions using available datasets, for use in Fourth and Fifth Case Studies for postclosure safety of a deep geological repository.
- Determine the limitations of available datasets, and develop a plan for a reference dataset.
- Conduct measurements as appropriate to obtain solubility data for conditions relevant to the Canadian repository program.

3.4 CRITICALITY

Rationale for Future Work

In the original safety case studies in the 1990's, it was demonstrated that the risk of criticality of used CANDU fuel in repository was not credible. However, the current used fuel container design (IV-25, Chapter 5) contains a larger fuel inventory (and therefore plutonium inventory) than previous designs (i.e., 360 bundles vs 72 bundles) and a different fuel basket configuration. Also, since the use of enriched uranium fuels is being considered, criticality assessments for these fuels may also be necessary. Criticality analyses are also required for the non-standard research fuels and fuel materials from AECL that need to be placed in a geological repository.

Work Program **B**

Updated criticality analyses for used fuel will be undertaken using current methods to ensure that the current container and repository concepts remain well below criticality limits.

3.5 FUEL INTEGRITY

Earlier investigations have concluded that used CANDU fuel is unlikely to suffer significant degradation during an extended period of dry storage (100 years), since most of the known fuel degradation mechanisms are not active under the conditions in which it is stored in Canada (Byrne and Freire-Canosa, 1984; Lovasic and Villagran, 2004; Lovasic and Gierszewski, 2005). However, the endcap/endplate welds, which are important structural components of the CANDU fuel bundle, may be susceptible to deterioration caused by delayed hydride cracking (DHC). A series of tests were conducted during the period 2007-2010, designed to establish the threshold value of key parameters (stress fields, stress intensity factors) for DHC to occur, and to measure DHC crack velocities in CANDU fuel specimens.

These threshold values were then compared to predicted parameter values under dry storage conditions. For this purpose, a finite-element (FE) model of the CANDU fuel bundle was developed that can be used to calculate post-irradiation stress fields and stress intensity factors in the endcap-endplate weld region of a bundle. This allows the prediction of the bundle long-term behaviour and provides information that can be used for the design of long-term storage and fuel handling systems.

3.5.1 Development of the CANDU Bundle Stress Model

The bundle stress model was developed using the ANSYS Finite-Element Analysis software and describes typical 28- and 37-element CANDU fuel bundles. The complex bundle geometry resulted in a large FE model consisting of approximately 100,000 elements (Figure 3.9). Experiments were conducted to validate the results of the modelling and test how well the model predicts fuel bundle behaviour. Results from tests conducted on 28-element and 37-element unirradiated fuel bundles indicated that the model is an adequate tool to assess fuel bundle behaviour during dry storage. Details of the validation of model results are reported in Lampman et al (2008, 2009).

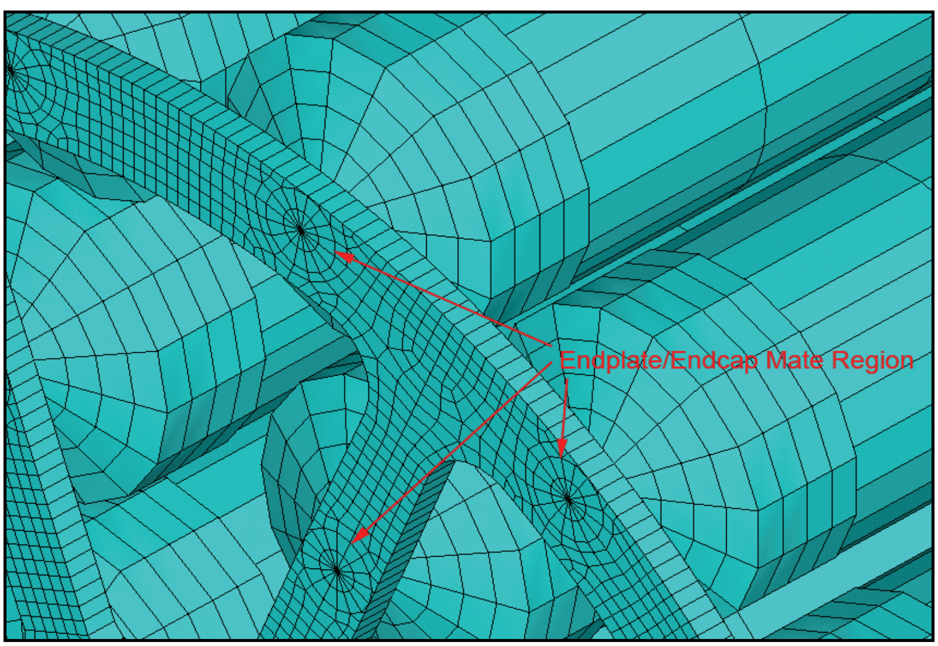

Figure 3.9: Detail of CANDU Bundle Stress Model Finite-Element mesh

3.5.2 DHC Testing of Endplate/Endcap Welds

Material properties such as the threshold stress intensity factor (K_{IH}) for DHC crack initiation and DHC crack velocity (DHCV) for Zircaloy endplate/endcap assembly welds are key parameters to assess the significance of DHC during the dry storage of CANDU fuel bundles.

An apparatus to test irradiated endplate/endcap welds was designed and tested using non-irradiated CANDU fuel bundle specimens. The apparatus was designed to have the test samples loaded in a cantilever bending system such that a tensile stress is applied to the weld. Depending on the magnitude of the load applied, the resulting tensile stress can initiate and propagate a crack at the endplate/endcap weld notch.

Tests on non-irradiated fuel were conducted to determine stress intensity factors (K_{IH}) and DHC crack velocities in order to establish whether DHC could be operative under dry storage of the used fuel. A series of tests were performed on several endplate/endcap welds to gather data on the DHC cracking. Metallography and SEM were subsequently performed on cracked weld samples to establish if the rupture was due to DHC. These tests were conducted at 130^{o}C and 150^{o}C, which represent the expected upper temperature limit during dry storage. The test samples were prepared from a non-irradiated commercial 37-element CANDU fuel bundle with an “as received” 10 ppm hydrogen concentration in the endplate/endcap welds. In order to attain hydrogen concentrations relevant to irradiated fuel bundles, hydrogen was added electrolytically to the bundle assembly welds to a concentration of 40 ppm.

In the DHC tests, both analytical and FE stress analysis methods were used to determine the stress intensity factor K_I at the weld discontinuity as a function of the applied bending load. The results of these calculations yielded K_{IH} values in the range of 7.6-13.6 MPa.m$^{1/2}$ and DHC crack velocities in the range of 1.8 x 10^{-9} to 6.8 x 10^{-10} m/s for the tested samples. The K_{IH} values are comparable to values of 8 to12 MPa.m$^{1/2}$ reported by Ambler (1984) for irradiated Zircaloy electron beam welds. The crack velocity values also appear reasonable when compared to values of 8 to 9 x 10^{-9} m/s available from testing of Zr-2.5 Nb pressure tube material. Additional tests on commercial CANDU fuel bundles to establish the sensitivity of the K_{IH} and DHCV values to bundle type and manufacturing process were also performed. These tests expanded the database and confirmed the previously found K_{IH} and DHCV values.

State of Knowledge

Based on validation and verification tests of the Bundle Stress Model conducted in 2009, improvements to the model were implemented (Lampman et al. 2009). Bending load tests were also performed on single fuel elements from typical 28- and 37-element CANDU fuel bundles. It was found that the improved version of the Bundle Stress Model provided accurate predictions of the fuel element behaviour. The test results indicate that DHC as a degradation mechanism is not expected to be operative in irradiated CANDU fuel bundles during dry storage, since stress levels under dry storage conditions will be significantly lower than the values required to either initiate or propagate DHC in non-irradiated CANDU fuel.

Work Program **B**

The findings from this program, which was completed in 2010, indicate that DHC will not affect the long term integrity of CANDU fuel in dry storage. The results will be summarized in a 2011 NWMO Technical report.

4 REPOSITORY DESIGNS

The Canadian used nuclear fuel waste management program has developed a number of conceptual designs and used fuel container placement methods for a deep geological repository in crystalline rock (AECL 1994, Baumgartner et al. 1996, CTECH 2002, RWE NUKEM 2003, SNC-Lavalin 2011a) and in sedimentary rock (RWE NUKEM 2004, SNC-Lavalin 2011b).

The repository concept entails encapsulating used fuel bundles in durable containers and sealing the containers in a repository located at a depth of around 500 m in a stable geological formation. The APM facility comprises surface facilities, where the used fuel is encapsulated, and a number of shafts that provide access and ventilation to a network of horizontal tunnels and placement rooms in the deep geological repository where the used fuel containers will be isolated. The facility will be designed to suit the structure and characteristics of the host rock, the groundwater flow system and other subsurface conditions at the particular site. A conceptual design for crystalline rock is illustrated in Figure 4.1 and further described in Section 4.1. A repository conceptual design for sedimentary rock is described in Section 4.2.

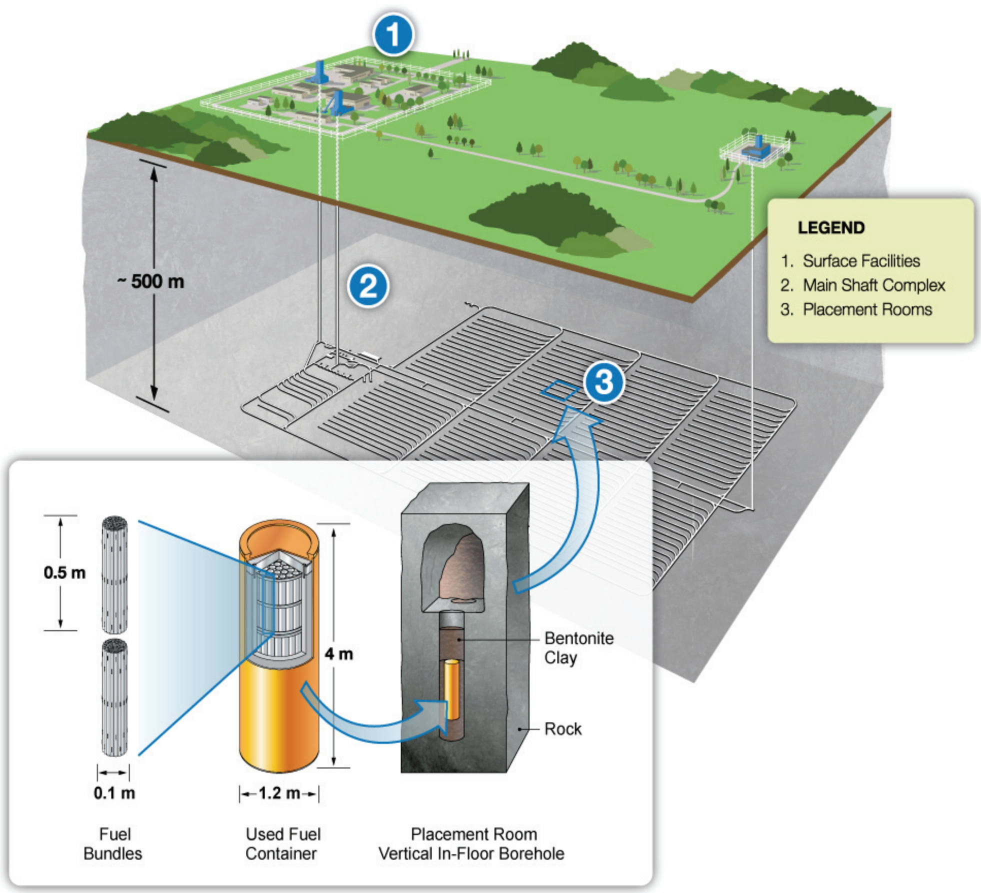

Figure 4.1: Conceptual design of a deep geological repository for used nuclear fuel using the vertical in-floor borehole configuration.

NWMO's current conceptual designs for a deep geological repository for used nuclear fuel incorporate a system of multiple engineered barriers for containment of the fuel that include the used fuel container and the repository sealing systems. Depending on the particular design, the used fuel containers may be placed either horizontally within the placement rooms or in boreholes drilled from the rooms. Clay-based sealing materials are used to surround the containers and to fill the remaining voids in each placement room to ensure low-permeability as well as chemically and biologically benign conditions. The near-field rock mass surrounding the repository will be altered during both construction and operation of the repository. The altered characteristics of this volume of rock are considered in the engineering performance analysis and safety assessment of the repository.

After each placement room is filled with a specified number of used fuel containers and backfilled, a room seal and a concrete bulkhead will be placed near the room entrance. After the placement rooms are full and sealed, the repository performance will be monitored for a period of up to 70 years or more. Then, following the appropriate consultations and required regulatory approvals, the repository tunnels, shafts, ramps and service areas will be backfilled and sealed. This operation will mark the end of the repository operating life and it is called repository closure. The repository is designed for passive safety, which means that its design features ensure that postclosure safety of the facility does not depend on institutional controls.

The repository concept also includes provisions for retrieval of a used fuel containers during the preclosure period, if this became necessary, as well as provision for postclosure monitoring of the repository and its surroundings, and a feasible approach for postclosure retrieval of used fuel containers.

4.1 DESIGN FOR CRYSTALLINE ROCK

State of Knowledge

Based on Canadian and other national conceptual design studies, various methods for container placement in a deep geological repository have been identified for crystalline, hard sedimentary rock and soft sedimentary rock (Maak et al. 2010). The in-floor borehole placement method, which has been selected for crystalline rock for conceptual design and cost estimating purposes, has been extensively studied in Canada, Sweden, Finland and Japan as part of the development of repository concepts in crystalline rock (e.g. AECL 1994, Vieno and Ikonen 2005, SKB 2007, Andersson 2007).

SKB (Sweden), with the cooperation of Posiva Oy (Finland) and other nuclear waste management organizations, has been conducting large-scale experiments at the Äspö Hard Rock Laboratory (HRL) in Sweden to develop and demonstrate appropriate technologies for construction and operation of a deep geological repository in crystalline rock. These experiments include full-scale demonstration of used-fuel container and sealing system placement technologies as well as some aspects of the technology for used fuel container retrieval.

For the in-floor borehole placement method, the used fuel container is placed vertically into a borehole drilled in the floor of a placement room as shown in Figure 4.1. The borehole dimensions are a function of the container dimensions and the required thickness of sealing material, which consists normally of highly compacted bentonite (HCB). For example, for the IV-25 and the IV-324-hex containers (see section 5.1) with external dimensions of approximately 1.2 m in diameter and 3.9 m in length, the required dimensions of the borehole are about 1.9 m in diameter and 6.9 m in length. This results in a minimum thickness of about 35 cm of sealing materials between the container and the rock.

The used fuel containers are surrounded by blocks of HCB configured as discs and rings. The gap between the container and the HCB blocks, and the gap between the blocks and the rock wall are filled with HCB in granular form, which is referred to as gap fill material. Additional HCB discs are placed both below and above the used fuel container and with the upper two disks in the in-floor borehole formed from dense backfill (DBF). Once all boreholes in a placement room are filled, the room is backfilled using blocks of DBF surrounded by light backfill. Then the room is then sealed with a bulkhead. The backfill materials (described in detail in Table 5.2) consist of compacted mixtures of bentonite and sand or bentonite and crushed rock.

Alternative conceptual designs for a deep geological repository have also been considered in the Canadian program and a number of options appear to be viable based on evaluation of repository concepts being developed by other national radioactive waste management organizations (Maak et al. 2010).

Rationale for Future Work

The site for a Canadian deep geological repository for used nuclear fuel may be located in crystalline rock. The reference conceptual design, cost estimate and safety case for a deep geological repository in crystalline rock will be updated in 2011 to support the repository siting process (SNC-Lavalin 2011a). Further work on conceptual repository designs and options in crystalline rock will be required to ensure NWMO has the appropriate level of engineering design and safety to support licence application following the planned selection of a preferred site by 2018.

Work Program A

NWMO will prepare a conceptual design and a cost estimate for a deep geological repository constructed in crystalline rock with a generic geosphere similar to that assumed for the Third Case Study for postclosure safety assessment (Garisto et al. 2004). This work will be documented in 2011. A safety assessment based on this conceptual design will also be conducted. Further development of repository designs including various container placement options in crystalline rock and the potential for a multi-level repository will continue along with the preparation of associated safety case studies.

4.2 DESIGN FOR SEDIMENTARY ROCK

State of Knowledge

The Canadian concept for a deep geological repository in hard[1] sedimentary rock is examining the horizontal tunnel placement method, which is similar to the Nagra tunnel placement method. The development of the horizontal tunnel placement method can draw from related information from Nagra’s repository development program in Opalinus clay in Switzerland.

As shown in Figure 4.2, the horizontal tunnel placement method consists of placing the used fuel container in a horizontal orientation in a room surrounded by a buffer sealing system which consists of an HCB pedestal to support each container and HCB pellets to fill the remainder of the void space. The simple geometry of the horizontal tunnel placement method makes it easier to model and assess the thermal, hydraulic and mechanical behaviour of the repository.

[1] Hard sedimentary rocks have a low rock creep rate and will not affect excavation stability during the operational period of the repository. Excavation stability will be influenced by in situ rock properties and in situ stress.

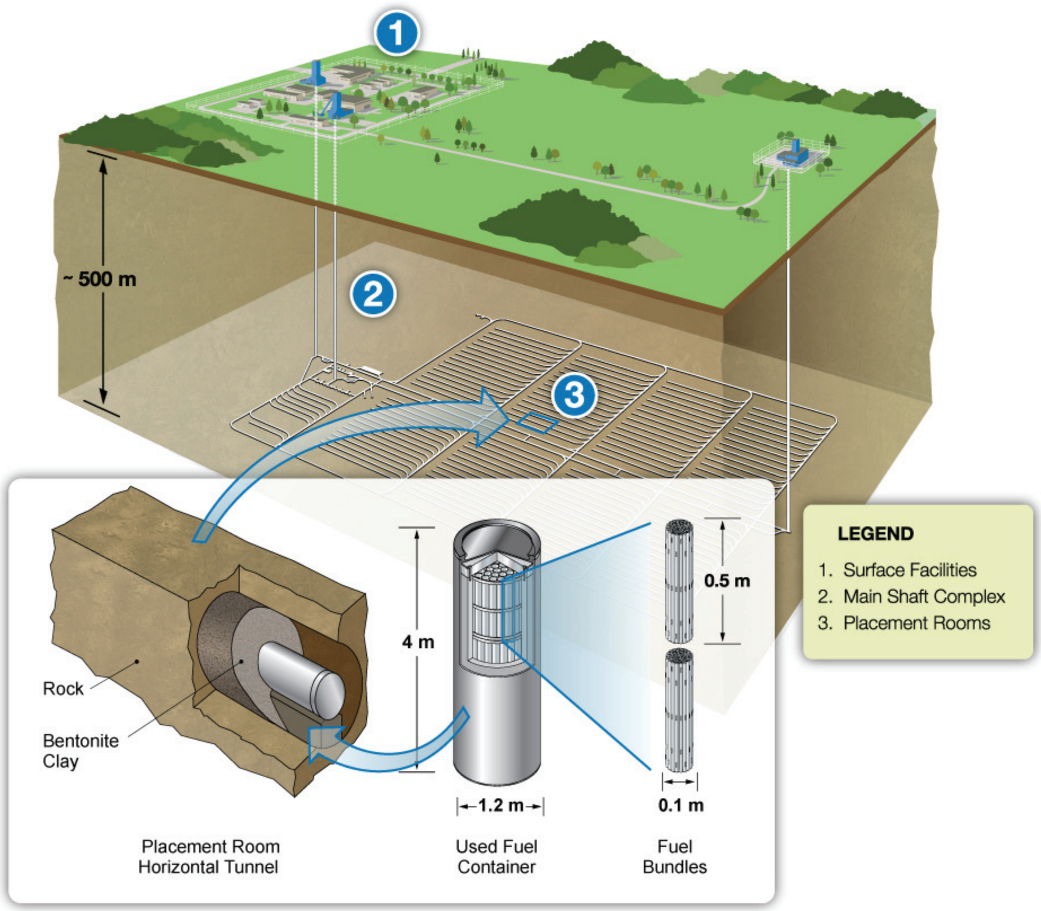

Figure 4.2: Conceptual design of a deep geological repository using the horizontal tunnel configuration.

In the case of a deep geological repository sited in soft[2] sedimentary rock, a container placement methodology such as the Nagra tunnel placement method with a rock liner or the ANDRA horizontal tunnel placement method which employs a sealing system that consists of a steel tunnel liner, large highly-compacted buffer blocks and an inner steel sleeve could be considered.

Rationale for Future Work

The site for a Canadian deep geological repository for used nuclear fuel may be located in sedimentary rock. The reference conceptual design, cost estimate and safety case for a deep geological repository in sedimentary rock will be updated by 2013. Further work on conceptual repository designs and options in sedimentary rock will be required to ensure NWMO has the appropriate level of engineering design and safety to support licence application following planned selection of a preferred site by 2018.

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[2] Soft sedimentary rocks have a high creep rate and will affect excavation stability during the operational period. Excavation stability can be maintained with rock support (e.g. liners).

Work Program **A**

NWMO will prepare a conceptual design and a cost estimate for a deep geological repository constructed in sedimentary rock based on the horizontal tunnel placement method. This work will be documented in 2011. A safety assessment based on this design will also be conducted. Further development of repository designs including various container options and sealing materials in sedimentary rock will continue along with the preparation of associated safety case studies.

4.3 NUMERICAL MODEL DEVELOPMENT AND APPLICATIONS

In support of the development of used fuel repository designs in both crystalline and sedimentary rock, NWMO has carried out a numerical modelling program to both develop numerical codes for the unique aspects of used fuel placement and to predict the performance of a deep geological repository under operating conditions, given the properties of the rock and bentonite-based sealing materials.

State of Knowledge

Numerical codes are used to simulate the Thermal-Hydraulic-Mechanical (THM) evolution of the used fuel repository and its surroundings, including the behaviour of clay-based sealing materials. In order to develop modelling practices and to calibrate the codes, numerical modelling has been used to simulate several large scale experiments conducted in underground research laboratories in Canada and Sweden. This included supporting the modelling tasks of the SKB Engineered Barriers System (EBS) Task Force; analyzing repository conceptual designs in NWMO specified host media, including the assessment of both near and far field conditions; and developing and maintaining capability to conduct TMH modelling of repository sealing systems in Canada.

Since 2005, Canada has participated in the international EBS Task Force co-ordinated by SKB (Sweden), whose objective is the development of tools for advanced coupled THM modelling of buffer and backfill. NWMO participates in the EBS Task Force modelling group through numerical modelling expertise in Canada. NWMO has also supported the development of the CODE_BRIGHT program for modelling the THM evolution of the used fuel repository with an emphasis on sealing system behaviour.

In 2007, two large in-situ experiments previously conducted by AECL at their Underground Research Laboratory (URL), the Buffer-Container Experiment (BCE) and the Isothermal Test (ITT), were used as case studies by the international modelling group. Guo (2007a) modelled these experiments according to the EBS Task Force specifications and provided comparisons of the results with measured data describing the THM evolution of the buffer and the surrounding rock (Dixon et al, 2001). The CODE_BRIGHT results matched well the measured data (Guo 2007a). Guo (2008) also carried out an analysis of aspects of SKB's Canister Retrieval Test as a component of the EBS Task Force. The results of numerical modelling have also been used to support the conceptual design of the used fuel repository.

A thermal sensitivity analysis of a deep geological repository constructed at a 750m depth in limestone using the Nagra tunnel placement method was conducted using CODE_BRIGHT (Guo 2008). This study investigated the influence of both tunnel and container spacing on container surface and rock surface temperatures in the repository tunnels. An example of the relationship between the thermal conductivity of the buffer and the container surface temperature for a specific tunnel and container spacing is shown in Figure 4.3.

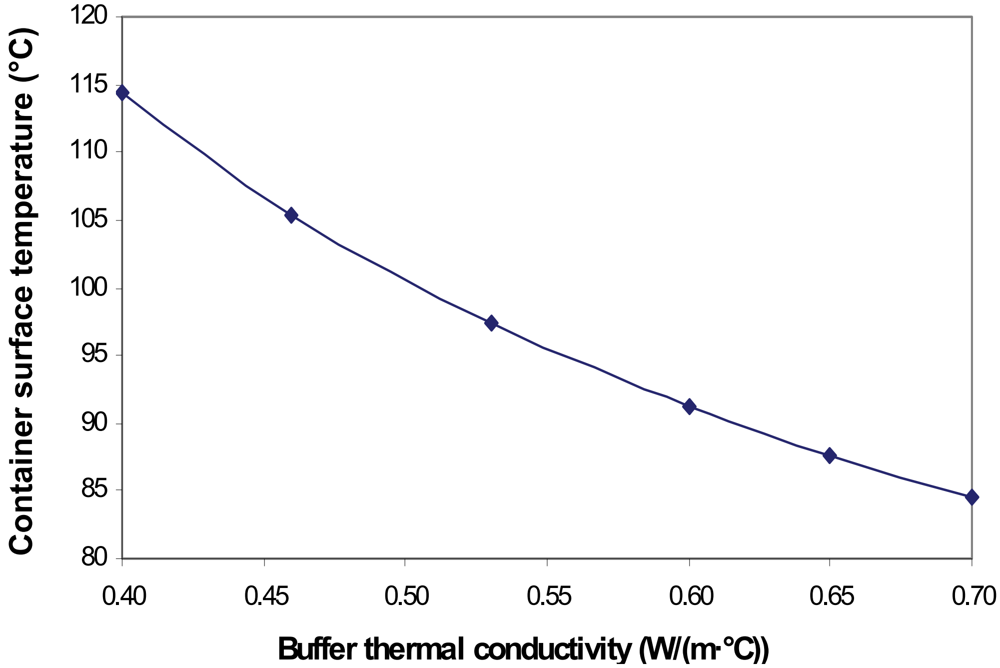

Figure 4.3: Container-Surface Temperature vs. Buffer Thermal Conductivity for a Case with a Tunnel Spacing of 24 m and a Container Spacing of 14 m.

Three-dimensional finite-element, thermal transient and TM stress analyses were performed to better understand the behaviour of the crystalline rock mass in the near-field and far-field of a repository using the in-floor borehole placement method (Guo 2007b). The results of the modelling using CODE_BRIGHT are in good agreement with the results of a previous assessment done by RWE NUKEM (2003) using the commercial code ABAQUS. Figures 4.4 and 4.5 show far-field temperatures and vertical displacement histories obtained from the analysis.

In 2008, numerical models of different used fuel repository configurations were developed. This work included models of the in-floor borehole and horizontal borehole container placement methods, and a thermal sensitivity analysis of the Nagra-type horizontal tunnel placement method.

Chandler (2008) used the Fast Lagrangian Analysis of Continua (FLAC) code for compliance modelling of both the in-floor borehole method and the horizontal borehole method to examine the density changes of swelling clay materials upon saturation. In both cases bentonite pellets were used as gap-fill between the used fuel container and HCB. The analysis results were used to establish the minimum gap-fill dry density required to achieve the final density needed to minimize microbial activity at the container surface (this is further discussed in Section 5.1.1.1).

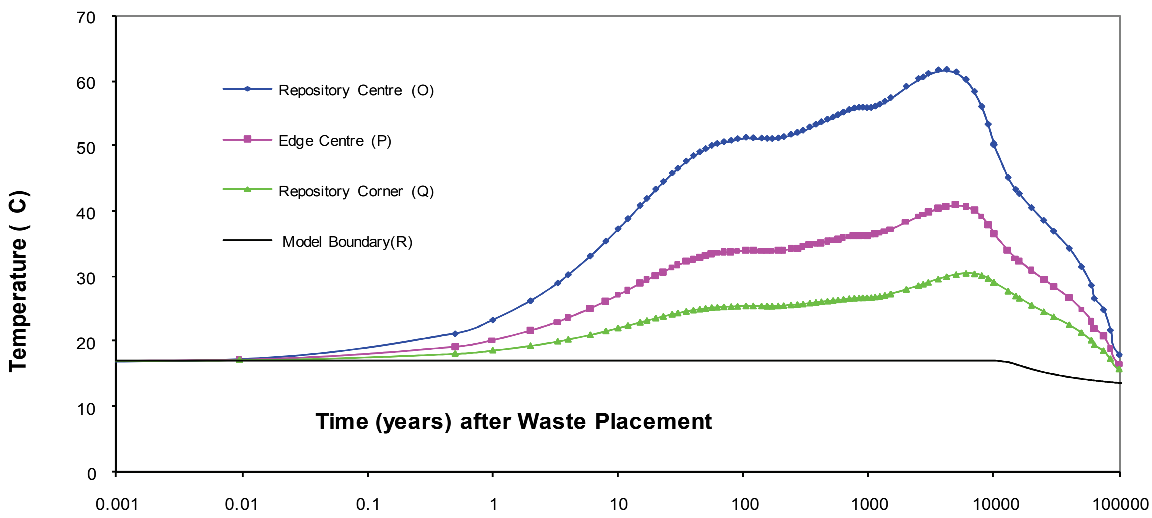

Figure 4.4: Far-field analyses temperature histories at four different locations.

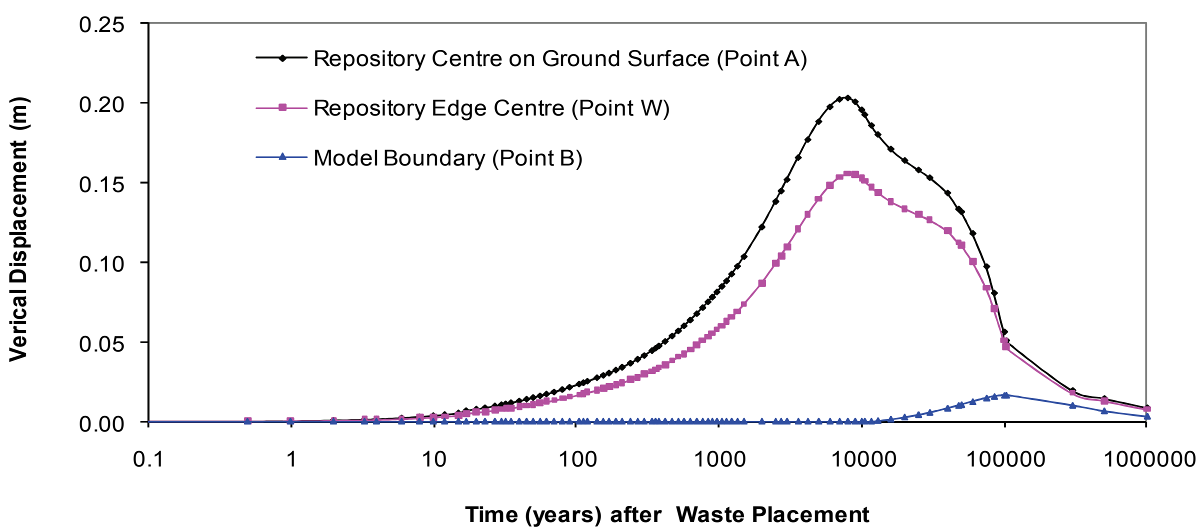

Figure 4.5: Thermally induced vertical displacements with time at three different locations on the ground surface (positive is upward).

Rationale for Future Work

Currently NWMO is updating its reference conceptual repository designs for crystalline rock and sedimentary rock. The tasks required to support repository design efforts include the development and maintenance of codes used for modelling the behaviour of engineered barriers and the definition of the placement room and used fuel container spacing.

Alongside with code development, NWMO participation in international studies aimed at developing and evaluating repository sealing systems is considered an essential on-going component of the Engineered Barriers work program, serving to benchmark both methods and results against the work of international teams.

Work Program A

During 2010, NWMO provided modelling input to international EBS Task Force co-ordinated by SKB (Sweden). In addition to contributing to international joint programs, NWMO is conducting THM analyses of a repository using the in-floor borehole container placement method at a depth of 500 m in sparsely fractured crystalline rock using CODE_BRIGHT, COMSOL and FLAC.

Further modelling support to international programs on repository development is planned over the next 5 years. As well, NWMO will carry out detailed analyses for the design of a deep geological repository using the horizontal tunnel placement method in sedimentary rock at a depth of 500 m.

4.4 REPOSITORY MONITORING AND CONTAINER RETRIEVAL

APM includes monitoring of repository performance as well as monitoring of the impacts of a deep geological repository on the environment. The repository designs being developed include provisions to ensure that used fuel containers can be retrieved throughout all phases of APM implementation (NWMO 2005). NWMO is continuing to conduct work on both monitoring and container retrieval methods.

Within the context of APM, monitoring can be divided into two categories: (i) environmental monitoring, which includes monitoring of processes and parameters in both the biosphere and the geosphere, and (ii) monitoring the performance of the repository systems, both during and after used fuel placement, in order to confirm the performance of the repository. Environmental monitoring will be initiated as soon as a preferred site is selected. Repository performance monitoring will evolve through the different phases of development of the APM facility. The latter system will be developed in parallel with the planned underground demonstration facility, although some of its components will start operating during the site characterization phase.

In developing repository designs, NWMO is considering the requirement to ensure retrievability of the used fuel containers and is examining the aspects of retrieval that might require technology development to ensure that the retrievability of used fuel containers will not compromise the ultimate safety of the deep geological repository.

State of Knowledge

A substantial body of knowledge on monitoring technology has been developed in Canada associated with the construction and operation of AECL's Underground Research Laboratory (URL) in Manitoba. Experiments conducted at the URL during its operating life have involved the monitoring of parameters relevant to repository performance (Baker, C. 2002; Martino and

Simmons, 2006; Martino et al, 2008) and the development, testing and demonstration of monitoring instruments and equipment for a repository have been underway for many years (Thompson et al, 2003; Dixon et al. 2004; Dixon et al, 2009). The performance and longevity of many monitoring instruments have been tested in underground research facilities including the AECL URL in Canada. Also innovative technologies for both repository monitoring and UFC retrieval are being developed and demonstrated at various facilities such as the Äspö Hard Rock Laboratory in Sweden, the Mont Terri Project in Switzerland, the Bure URL in France and the HADES URL in Mol, Belgium.

The Canister Retrieval Test at the Äspö Hard Rock Laboratory is one example of full-scale demonstration of used fuel retrieval technology (SKB 2007). Monitoring and used fuel retrieval are expected to continue being areas of co-operative research, development and demonstration for NWMO and other national radioactive waste management organizations.

Rationale for Future Work

The methods and technologies required for container retrieval, as well as the criteria required to make the decision to retrieve a used fuel container need to be developed along with the repository designs. Repository monitoring systems and design provisions for retrievability of the fuel waste need to be developed to ensure that the appropriate methods for removal of used fuel waste from the repository can be effectively implemented if required. These methods and technologies need to be developed along with the development of repository designs.

Retrieval Work Program **B**

NWMO will stay abreast with the development of the latest retrieval technologies and demonstration trials performed in other national nuclear waste management programs such as SKB's planned joint project, Retrieval of the Prototype Repository at Äspö Hard Rock Laboratory, 2011-2013. In parallel to developing the technical aspects of retrievability of radioactive waste, NWMO will also continue to participate in international working groups to monitor the non-technical aspects (e.g. ethical, safeguards, allocation of responsibility for retrieval) of retrievability and recoverability.

Monitoring Work Program **B**

Conceptual designs of systems related to repository monitoring will be developed as an integral part of APM implementation. An overall monitoring strategy, along with relevant system design requirements will be developed in parallel with the repository design evolution process. The monitoring program activities will include reviewing and documenting the monitoring results from the Enhanced Sealing Project (described in Section 5.2.4), conducting a technical assessment of monitoring requirements for repository designs in crystalline and sedimentary rock, and a review of monitoring methods being developed and evaluated by international projects.

Monitoring system development will be conducted in parallel with NWMO's repository design optimization. This will include the identification of the set of parameters to be monitored and of technologies to be evaluated and demonstrated. These tasks will be based on the state of the science and will include continued participation in Canadian and international projects. Progress in the above areas will be documented in NWMO technical reports. In parallel, documents that will serve as a basis for discussion of monitoring objectives and methods with external stakeholders will also be prepared.

5 ENGINEERED BARRIERS

The NWMO's Technical Program includes advancing the technologies associated with a used fuel deep geological repository that might be sited in either crystalline or sedimentary rock. The repository designs being developed are based on a multi-barrier system approach, comprising a combination of engineered and natural barriers that will provide containment and isolation of the used fuel from the biosphere for a very long period of time (Russell and Simmons, 2003). The fuel structure itself constitutes the first barrier to release of the radionuclides to the environment. The barriers that are part of the repository include the used fuel, used fuel container, the repository sealing systems and the host rock (geosphere). The container, the sealing materials placed around the container, and the repository seals constitute the engineered barriers.

5.1 CONTAINER DEVELOPMENT

Several types of potential used fuel container designs are being considered by the NWMO. The current reference conceptual design is a double-shell container consisting of an outer copper corrosion-barrier vessel and an inner carbon steel load-bearing vessel (see Figure 5.1). An alternate used fuel container conceptual design consists of a single steel vessel that provides both the corrosion resistance and the mechanical strength required for a long service life in the repository. Other container designs are also possible in a deep geological repository. The current reference and the alternate container designs are described below.

5.1.1 Copper Container Design

State of Knowledge

SKB (Sweden) and Posiva (Finland) have well-developed copper container designs and associated technologies for a deep geological repository in crystalline rock. Currently, the reference Swedish and Finnish container designs have 50 mm-thick copper vessels with a cast-iron insert. The outer shell is made of high-purity, oxygen-free, phosphorous-doped (OFP) copper. The phosphorus is added to the copper to increase the creep ductility, making the copper vessel more resistant to conditions that might lead to creep rupture.

A number of copper container geometries and capacities have been developed for the NWMO repository concepts (Maak and Simmons 2001, Poon et al. 2001). Several copper container conceptual designs, e.g., the IV-25, IV-324-hex and IV-17 designs have been considered for the development of repository designs and for APM cost estimating purposes. These particular container designs consist of an outer 25-mm-thick copper vessel, an inner carbon-steel vessel and used fuel baskets. The IV-324-hex was used for the 2003 conceptual design and cost estimate update (RWE NUKEM 2003, 2004) and the IV-25 design for the 2010 update (SNC Lavalin 2011a). The IV-324-hex design holds 324 fuel bundles in six layers of 54 bundles. The fuel is placed inside the container packaged in three baskets containing 108 fuel bundles each (Figure 5.1). The IV-25 holds 360 fuel bundles in 6 layers of 60 bundles.

Other container geometries with similar characteristics to the previous designs include the IV-17-T50, a variation of the IV-17 design with a change in the thickness of the outer copper vessel from 25 mm to 50 mm. Both container designs hold 288 fuel bundles in 8 layers of 36 bundles. The dimensions of these two container designs are given in Table 5.1. The configurations of the IV-324-hex container and its 108-bundle fuel basket are shown in Figure 5.1. The inner steel vessels of these containers are designed to withstand the following postulated external isotropic loads in a deep geological repository: a pre-glaciation load of 15 MPa and a maximum load of 45 MPa during glaciation cycles.

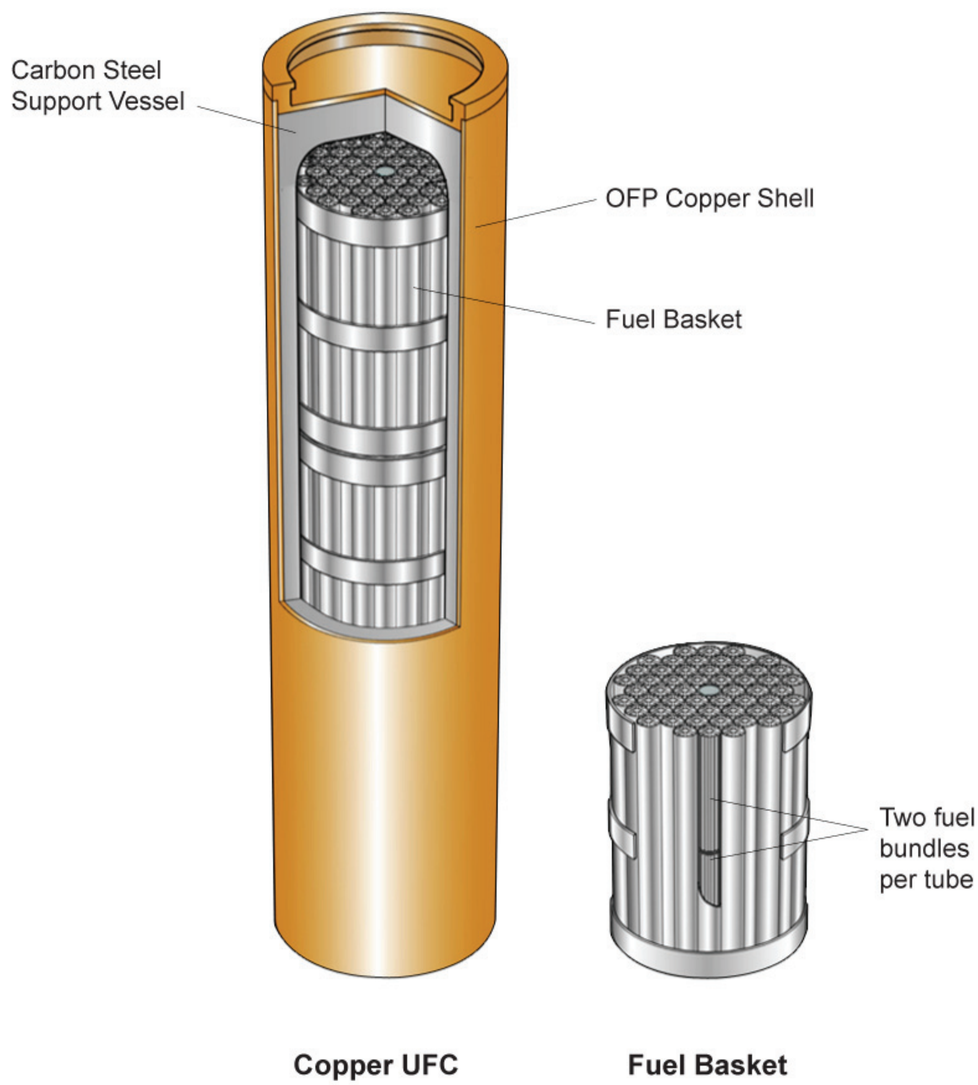

Figure 5.1: Copper Used-Fuel Container (IV-324-hex) and Fuel Basket holding two layers of 54 fuel bundles each in a hexagonal tube array.

The maximum gamma dose rate at the outer surface of the copper vessel is estimated to be less than 0.09 Gy/h (Hanna 2001). This is an order of magnitude below the upper limit of 1 Gy/h (Werme 1998, Raiko 2005) considered necessary to limit the radiolytic production of corrosion agents near the container surface. Thermo-mechanical analyses indicate that it is possible to develop thermally and structurally acceptable repository layouts using the IV-324, the IV-25 and the IV-17 container designs.

Table 5.1: Design Configurations of a Used Fuel Container

	IV-25[a]	IV-324-hex[a]	IV-17[a]	IV-17-T50[b]
Container Fuel capacity	360	324	288	288
Number of bundles per layer	60	54	36	36
Copper vessel outside diameter (mm)	1247	1168	984	1035
Copper vessel height (mm)	3,909	3,867	4,744	4,794
Copper vessel shell thickness (mm)	25	25	25	50
Mass of empty copper vessel (kg)	4,165	3,824	3725	7229
Steel vessel outside diameter (mm)	1,195	1,116	932	932
Steel vessel height (mm)	3750	3708	4585	4585
Steel vessel shell thickness (mm)	102.5	96	80	80
Mass of empty steel vessel (kg)	12,649	1,0816	8,768	8,768
Mass of container with fuel (kg)	26,699	23,537	20,401	23,905
Number of containers required for 3.6 million bundles	10,000	11,110	12,500	12,500
Number of containers required per year for an 30-year repository operation period	334	371	417	417

a. Container data extracted from Maak and Simmons (2001)
b. The container data for IV-17-T50 are derived by extrapolation of data from IV-17

Rationale for Future Work

The used fuel container is a key engineered barrier in the APM repository conceptual design. The current range of potentially suitable used fuel container designs needs to be further studied, reviewed and evaluated to develop the generic reference design for a repository site.

Work Program **A**

NWMO's technical program is focussed on developing repository designs including work to advance the design of a copper used fuel container. The work program will review and assess the potential range of practical container design options, geometries and capacities for used CANDU fuel in a deep geological repository and further advance viable container designs considering various evaluation factors such as fabrication technology, corrosion performance, handling, interface with underground design and cost.

The following sections discuss some key aspects of the design of a copper used fuel container.

5.1.1.1 Copper Corrosion

State of Knowledge

A review of current knowledge on copper corrosion was conducted by the NWMO in 2007 (King, 2007). The state of knowledge on uniform corrosion, pitting, stress corrosion cracking (SCC) and microbiologically-influenced corrosion (MIC) of copper is described below.

Uniform Corrosion

A model was developed for predicting the uniform corrosion behaviour of copper containers in a deep geological repository (King 1996, King and Kolar 2000). The maximum wall thickness loss caused by uniform corrosion, calculated based on the inventory of trapped oxygen (O_2) in the repository, is about 80 μm. Corrosion due to sulphide, either from groundwater or from impurities in the clay, or possibly from microbial activity, is calculated on a mass-transport basis and it accounts for an additional 0.27 mm over a period of 10^6 years.

Pitting

Although the copper container is not expected to undergo pitting corrosion in the classical sense of the term, a form of non-uniform corrosion is expected to occur characterized by the temporary spatial separation of anodic and cathodic sites on the copper surface (King 2007). This type of localized corrosion is assessed by applying an empirical factor to the uniform corrosion depth. This factor is based on statistical analysis of empirical data and is assigned values between 2 (considered realistic) and 5 (conservative). Therefore, the total predicted pit depth in the copper vessel wall after 10^6 years will be in the range of approximately 1.5 to 2.0 mm.

SCC

Stress corrosion cracking (SCC) experiments have been conducted to determine the effect of oxidant, SCC agents (nitrite, ammonia and acetate) and chloride on the SCC behaviour of copper containers in a deep geologic repository (Ikeda and Litke, 2000). A model has been developed to predict the SCC behaviour of a copper container in a repository (King and Kolar 2005). The findings from both experiments and modelling indicate there is minimal risk of SCC of copper containers in a deep geological repository since the production and supply of SCC agents to the container surface will be very limited. A limited supply of oxygen in the sealing materials would further restrict the time period that a copper container might be susceptible to SCC. The susceptibility of copper to SCC would also be suppressed by the presence of chloride in the groundwater.

MIC

One of the key performance requirements of the repository sealing system is to suppress microbial activity at or near the used fuel container surface in a deep geological repository. Microbial investigations at the AECL Underground Research Laboratory have found that heterotrophic aerobes, anaerobes and sulphate-reducing bacteria were present in the buffer, backfill and sealing materials studied, and indicated that a 100% bentonite buffer directly in contact with the UFC's is necessary to reduce microbial activity to insignificant levels (Stroes-Gascoyne 2010). Since microbial activity can cause MIC, which may affect the service life of used fuel containers, a series of experiments were conducted with 100% highly compacted bentonite (HCB) to identify repository conditions and possible design provisions that might be required to suppress microbial activity and prevent MIC of copper containers in a repository (Stroes-Gascoyne et al. 2007, 2008, 2010a; Stroes-Gascoyne and Hamon 2010).

For a low-salinity repository environment (NaCl <50 g/L), a HCB with a dry density of 1.6 g/cm^3 is required to suppress microbial activity (Stroes-Gascoyne et al. 2007). At this dry density, the water activity of <0.96 and the bentonite swelling pressure of > 2 MPa appears to suppress microbial aerobic culturability below background levels (2.1 x 10^2 colony-forming units/g) in as-purchased bentonite (Stroes-Gascoyne et al. 2010b). In a high-salinity repository environment, the presence of chloride becomes the dominant factor limiting MIC, since it would suppress microbial activity over a wider range of bentonite dry densities (~ 0.8 to 1.8 g/cm^3) and a wide range of bentonite swelling pressures (Stroes-Gascoyne et al. 2007). Microbial studies assessing the effect of salt concentration on microbial culturability suggest that decreased culturability of aerobic microorganisms occurs with both $NaCl_2$ and $CaCl_2$ concentrations of ≥ 50 g/L (Stroes-Gascoyne et al. 2008, 2010a).

Experiments were also conducted to assess the effect of elevated temperature (60 to 130°C) and dry density on microbial viability and culturability (Stroes-Gascoyne and Hamon, 2010c). Cells were not particularly sensitive to a temperature of 60°C and some culturability remained after exposure to 80°C at all dry densities. At temperatures ≥ 121°C, culturability was reduced in both low and high density bentonite samples. However, the effect of temperature on culturability in low dry density bentonite was reversible once the heat source was removed and re-saturation was allowed to occur, highlighting the importance of maintaining high dry density to keep microbial activity to a minimum (Stroes-Gascoyne and Hamon 2010).

A MIC model developed by King and Kolar (2006) suggests that the amount of sulphide, nitrite, ammonia and acetate produced by microbial activity in the repository that could reach the container surface is likely to be very small and would not result in a significant amount of corrosion of the copper containers.

Rationale for Future Work

An extensive experimental and modelling program has been carried out on the corrosion of copper used fuel container in Canada over the past 20 years (King and Kolar 2000, King 2007). Experimental studies have focussed on uniform corrosion and stress corrosion cracking (SCC). Modelling studies have addressed uniform and localized (pitting) corrosion, SCC, microbiologically influenced corrosion (MIC), and predictions of the evolution of environmental conditions within a deep geological repository in crystalline rock formation.

It is expected that for a deep geological repository in sedimentary rock the groundwater salinity, and therefore the buffer porewater salinity, will be significantly higher. The sedimentary rock would likely have a lower permeability than crystalline rock, which would result in longer saturation times for buffer and backfill. Therefore, the corrosion behaviour of copper containers in higher salinity environment and longer periods of exposure to partially saturated sealing materials will need to be further investigated.

The corrosion models developed for estimating the corrosion performance of copper containers in a crystalline rock environment are based on customized computer codes. To enhance future NWMO modelling capability, it is planned that the existing corrosion models will be converted to a platform that is compatible with NWMO's software framework. Model modifications will also be carried out to include the prediction of copper performance in higher salinity and longer unsaturated environments.

Work Program **B**

The copper corrosion program will include the following tasks:

a) Prepare a close out report on corrosion of copper containers under anticipated low salinity crystalline rock environmental conditions, summarizing the detailed knowledge gained in the copper corrosion studies performed.

b) The existing corrosion models for predicting uniform corrosion, SCC and MIC of copper containers in a deep geological repository will be converted to the COMSOL platform. Plans include model modifications to account for the higher salinity and longer unsaturated environmental effects on copper corrosion.

c) Review any knowledge gaps of corrosion behaviour of copper in high salinity geological environments and the potential effects on the long-term performance of the EBS. Based on the review, a path forward for further corrosion studies of copper in sedimentary rock environment will be defined.

5.1.1.2 Creep Behaviour

State of Knowledge

There are two main aspects to container creep – an initial collapse of the copper shell onto the steel inner vessel, and then long term creep of the combined copper and steel system.

SKB (Sweden) has developed the oxygen-free phosphorous-doped (OFP) copper specifications for the used fuel container. The addition of a small amount of phosphorous improves the ductility of the copper, which is required to minimize the risk of creep rupture. SKB has conducted creep tests on OFP cold rolled and extruded copper tubes, electron beam welds and friction stir welds (Andersson et al. 1999, 2005 and 2007). Raiko (Raiko et al 2009) examined using finite-element analysis the container area considered most vulnerable to creep rupture and concluded that this is not a viable failure mechanism for their copper container.

Dutton (2006) calculated the total accumulated creep strain of the steel inner-vessel of the IV-25 container to be ~ $6x10^{-6}$ % after the used fuel container has been in the repository for 10^6 years. This deformation is considered to be too small to affect the steel vessel's long-term integrity and will also limit the long-term deformation of the outer copper vessel. Accordingly, the collapse of the copper shell onto the steel vessel is expected to result in limited creep strain, however, this should be confirmed via materials testing and finite-element analysis to determine the maximum values of localized creep strain at critical container locations.

Rationale for Future Work

It is important to be able to predict the creep behaviour of the copper shell during the various phases of the repository evolution, considering in particular the conditions to which the used fuel container might be subjected during the saturation period, the long-term changes associated with glaciation cycles, and the anisotropic loads that can result from rock displacements and earthquakes as well as stresses during container placement operations.

Finite-element models of candidate used fuel container designs need to be developed to analyze possible failure modes due to creep rupture. Detailed modelling of the potential deformation that the copper used fuel container will undergo under those conditions is required to assess the possibility of creep rupture. Additional data are required to develop the appropriate models, including the material data for container components specific to the proposed container designs.

Although some creep data exist from experiments conducted by Ho (2000) in a temperature range from 95 °C to 150°C using OFP samples from hot-rolled plate and electron beam welded material, a more extensive testing program will be required, over a wider range of temperatures, to extend the data from previous experiments and to address the requirements outlined above (SKB 2009b).

Work Program **B**

The timing and scope of future copper creep studies will be assessed as part of a used fuel container development plan over the next five years. During this period, NWMO plans to further advance generic repository and used fuel container designs, and any new copper creep tests will need to take this into consideration.

5.1.1.3 Copper Container Fabrication

State of Knowledge

SKB (Sweden) and Posiva (Finland) have conducted extensive development work on processes and methods for both fabrication and testing of their reference container designs, which consist of a 50 mm thick OFP copper shell supported by a cast iron insert (SKB 2007, Raiko et al. 2009). Both extrusion and pierce & draw methods have been demonstrated to be suitable for production of high quality seamless 50-mm-thick copper tubes with a diameter of 1050 mm. SKB has selected extrusion as their reference method for fabrication of copper tubes, and Posiva has selected pierce & draw as fabrication method for their copper shell.

In 2009 and 2010, NWMO investigation of methods for fabrication of copper vessels established that the extrusion process could not be applied using existing technology for fabricating the 25-m-thick copper tubes for potential used fuel container designs such as the IV-25 and IV-324-hex designs because an extrusion press of the required size is not currently available. The pierce & draw method was also found not to be practical for the IV-25 and IV-324-hex container designs using current technology. However, the roll forming of half-pipe sections combined with longitudinal welds appears to be a viable process using current technology for fabricating the 25-mm-thick copper tubes for these container designs.

The SKB reference method for sealing the 50-mm-thick copper container is friction stir welding (Andrew 2004 and SKB 2007); for Posiva, the reference sealing method for their copper container is electron-beam welding (Raiko et al. 2009). Full size lid welds of sound quality have been successfully made using both these processes. SKB and Posiva have also developed and demonstrated the use of ultrasonic, radiographic and eddy current methods for non-destructive testing of copper tubes and welds (SKB 2007, Raiko et al. 2009).

The inner steel vessels of the various copper container designs can be readily fabricated using conventional forming and welding methods currently used for fabricating pressure vessels

(Poon et al. 2001). A preliminary engineering assessment also indicates that the inner steel vessels can be potentially made using the sand casting technique (Poon and Maak 2004).

The used-fuel bundles are packaged in three steel baskets and then loaded into the inner steel vessel of the copper container, as illustrated in Figure 5.1. Each basket consists of an array of carbon steel tubes welded together in either a hexagonal array (IV-324 design) or a concentric-ring (IV-360) configuration. Two fuel bundles are placed into each tube. This system keeps the fuel bundles in a specific geometric configuration and prevents possible damage during basket loading and container handling operations.

Rationale for Future Work

The future steps in the development of a copper used fuel container need to include a full evaluation of container design options and technologies for fabricating copper containers which may include full-scale copper shells, inner vessels and used-fuel baskets as well as welding and inspection methods to be used for the container components.

Work Program **A**

NWMO will conduct a full review and evaluation of copper container design options and associated container fabrication methods and technologies as part of its planned work program in order to develop a generic reference copper container design for a future repository site.

5.1.2 Steel Container

Status of Container Design

NWMO is investigating the potential suitability of carbon steel as an alternate container corrosion barrier material for the design of a used fuel container in a deep geological repository (King 2005b). Currently, the focus of the work is on a carbon steel container for a repository in sedimentary rock, which may exhibit a lower hydraulic conductivity and would likely have higher salinity groundwater than a typical crystalline rock environment (Golder 2003, King 2005a). The current design of the carbon steel vessels is geometrically similar to the inner steel vessels of the IV-324-hex and IV-25 copper containers, whose dimensions are given in Table 5-1.

Rationale for Future Work

Development of the design for a carbon steel used fuel container for sedimentary rock was initiated in 2009. Well-developed manufacturing and testing technologies exist for carbon steel in a broad range of industrial applications. However, further research on carbon steel container fabrication and inspection technologies and on the long-term performance of carbon steel container designs under anticipated repository conditions is required as part of NWMO's planned container development program.

Work Program **A**

NWMO will conduct a full review and evaluation of steel container design options as part of its planned design development work program in order to develop a generic reference steel container design for a repository site.

Further details of planned research work on steel containers are provided in subsequent sections.

5.1.2.1 Steel Corrosion

State of Knowledge

The environmental conditions in a deep geological repository will evolve after closure as groundwater permeates from the surrounding rock into the repository and saturates the tunnels backfill and bentonite-based sealing materials over time. From the re-saturation viewpoint the container environment (near-field) will evolve through three phases which are characterized by the processes and properties listed in Figure 5.2

A repository built in a sparsely-fractured crystalline rock formation has been estimated to take from hundreds to thousands of years to become saturated, while a repository constructed in low-permeability sedimentary rock is likely to have a saturation period of perhaps many thousands of years (King 2007). The duration of the unsaturated period, during which corrosion processes are expected to be very slow, is a key parameter for predicting the container lifetime and could be especially important in the case of a repository constructed in sedimentary rock.

A comprehensive review of current knowledge on long-term corrosion behaviour of carbon steel under the conditions expected in a repository environment has been conducted by King (2007). The review included research on carbon steel containers by the national nuclear waste management organizations of Switzerland, Japan, Belgium and France, as well as other selected corrosion studies. The review identified knowledge gaps in the following areas:

1. Microbially influenced corrosion (MIC).
2. Uniform corrosion during the unsaturated, anaerobic period.
3. Evolution of corrosion damage.
4. Stress corrosion cracking (SCC).
5. Corrosion of welds and heat-affected zones (HAZ).
6. Hydrogen gas generation and hydrogen-induced degradation.

The review concluded that limited knowledge existed on both the corrosion rate of steel and the production of hydrogen under anaerobic, unsaturated conditions. As a consequence, experiments to study the corrosion behaviour of carbon steel and hydrogen generation under such conditions were initiated in 2008 and are currently in progress at the University of Toronto.

The corrosion rates of carbon steel specimens exposed to various environmental conditions (e.g. relative humidity, temperature, and salt coverage of the steel surface) are being measured based on the rate of hydrogen gas production. The evolution of H_2 is monitored by two different methods: (i) a high sensitivity pressure gauge system and (ii) a solid-state potentiometric hydrogen sensor capable of detecting hydrogen partial pressures as low as 10^{-6} bar (equivalent to a corrosion rate of 1.5×10^{-4} $\mu m.a^{-1}$). A study of the morphology of the corroded steel surface (from the anaerobic, unsaturated corrosion study) is also being conducted using various surface analysis techniques including X-ray Photoelectron Spectroscopy, Scanning Electron Microscopy, and Laser Raman Spectroscopy.

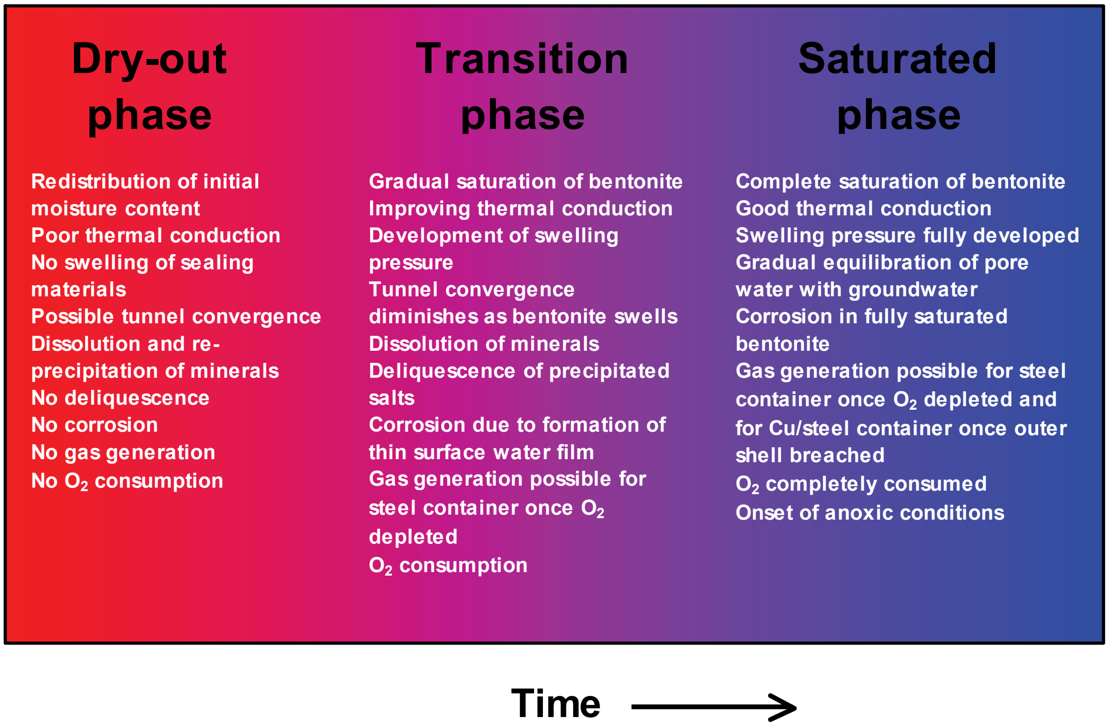

Figure 5.2: Evolution of conditions in a deep geologic repository characterized in terms of the different stages of saturation.

Rationale for Future Work

The lifetime for a used fuel steel container has previously been estimated to be between 1,000 to 10,000 years (Johnson and King, 2003). The duration of the unsaturated period and the corrosion rates during that period are important for improving the quality of estimates of the steel container lifetime, which may extend out to 100,000 years. This importance is enhanced in the case of a repository built in a low-permeability sedimentary rock environment, since low corrosion rates for an extended period of time mean a much longer containment and isolation of the waste form in the repository. Addressing the identified gaps in steel corrosion under unsaturated conditions and developing a predictive steel corrosion model that allows the evaluation of container lifetimes are, therefore, key required activities that impact both container design and safety case for the deep geological repository.

Work Program

A

Experimental and modelling studies relevant to carbon steel corrosion processes that consider container geometry and manufacturing process will be conducted in parallel with the steel container development.

A steel corrosion model (SCM) based on a series of one-dimensional reaction-transport equations has been developed by King and Kolar (2009). The SCM has the capability to predict the corrosion behaviour of the steel container as well as the impacts of corrosion products such as dissolved ferrous species and hydrogen on other components of the engineered barriers system (bentonite and bentonite/sand mixtures). Validation and verification activities for the SCM are continuing over the next few years.

Experimental research on steel behaviour under anticipated conditions in a deep geological repository in sedimentary rock has been initiated and the program will continue in parallel with the technology development program for the carbon steel used fuel container. As the container technology work advances and a detailed design is developed, corrosion assessments of the weld material and heat affected zones will be addressed.

5.1.2.2 Creep Behaviour

State of Knowledge

The long-term integrity of the steel used fuel container has been verified with respect to creep. Creep analysis for the inner steel vessel of a copper used fuel container concluded that under the postulated loads the inner steel vessel will experience a creep strain of ~ 6×10^{-6} % after the container has been in the repository for 10^6 years (Dutton 2006). Creep is, therefore, not anticipated to have significant effect on the long term integrity of the steel used fuel containers. No further work on creep of the steel vessel is planned.

5.1.2.3 Steel Container Fabrication

State of Knowledge

Conventional roll forming and seam welding of carbon steel used fuel containers appears to be a valid fabrication method. As well, previous feasibility studies concluded that an expendable-mold casting process would be suitable for fabricating steel vessel with a capacity up to 300,000 kg (Poon and Maak, 2004). Technical fabrication details were evaluated using a 3-dimensional commercial casting-modelling software (Magmasoft) and through consultation with industrial steel vessel manufacturers. Preliminary results from these evaluations indicate that it is technically feasible to sand-cast steel vessels with an integrated bottom or to sand-cast separate steel components (i.e., cylindrical steel shell, top lid, and bottom) and assemble components by welding. Seamless carbon steel pipes, as mentioned in Section 5.1.2, may also be available as a result of recent innovations at the steel mills. Such option would provide a more homogeneous container surface, mitigating the risk associated with weld corrosion.

Rationale for Future Work

A program to further develop the design and fabrication of carbon steel used fuel containers is required to determine the most appropriate method for application in a deep geological repository.

Work Program **A**

NWMO will conduct a review and evaluation of steel container fabrication technology as part of its planned work program in order to develop a reference steel container design for a generic repository site. This will include identification and evaluation of welding technologies to be used for the steel container manufacture.

5.1.2.4 Inspection Technologies

State of Knowledge

Carbon steel used fuel containers will be inspected by non-destructive testing methods. Three different methods for verifying the quality of the steel vessel have been evaluated: ultrasonic testing, magnetic particle inspection, and radiography (Poon and Maak, 2004). While ultrasonic testing is an effective method for detecting surface defects on the containers, an inspection process utilizing more than one non-destructive testing technique would significantly improve confidence and inspection efficiency (Saiedfar and Maak 2000).

Rationale for Future Work

Optimization of the specific testing technologies selected for the steel container manufacturing process will be needed for the container development program. Work is required to optimize the ultrasonic testing procedure as well as to develop at least one supplementary non-destructive testing method.

Work Program **B**

Techniques, including ultrasonic testing, eddy current testing and radiography will be further evaluated for their suitability as non-destructive testing methods for a steel used fuel container. Along with the assessment of the non-destructive testing methods, modelling will be conducted to determine test specimen configurations and to develop preliminary acceptance criteria for container welds.

5.2 SEALING MATERIALS DEVELOPMENT

5.2.1 Clay-Based Seals

NWMO is developing and demonstrating sealing systems for a used nuclear fuel deep geological repository. These studies have investigated the properties, long-term performance, and placement methods for various sealing systems, including clay-based materials and concrete. Since both crystalline rock and sedimentary rock are being considered as potentially suitable host geological media for a deep geological repository (NWMO 2005), a broad range of rock and groundwater chemistries need to be considered when evaluating the properties of specific sealing system materials.

State of Knowledge

Based on extensive work conducted by the Canadian nuclear waste program in previous years, a number of materials are currently being considered as components of repository sealing systems in Canada. These materials are described in Table 5.2.

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

Table 5.2: Repository Sealing Systems

Material Designation	Composition	Placement method
Highly Compacted Bentonite (HCB)	100% bentonite clay	Pre-formed, pre-compacted blocks of specific shape to suit the application are placed using mechanical handling equipment
Bentonite-Sand Buffer (BSB)	50% bentonite and 50% silica sand by mass	Pre-formed, pre-compacted blocks of specific shape to suit the application are placed using mechanical handling equipment
Dense Backfill (DBF)	70% crushed granite, 25% lake clay and 5% bentonite by mass	Placed as pre-formed blocks
Light Backfill (LBF)	A mixture of bentonite clay and crushed rock in the form of dense pellets. (e.g. 50% bentonite and 50% crushed granite)	Placed at low to medium dry density by pneumatic or mechanical methods
Gapfill (GF)	100% bentonite clay in the form of dense pellets	Placed at low to medium dry density by pneumatic or mechanical methods.
70/30 bentonite/sand shaft seal	70% bentonite, 30% sand by mass	Placed in layers and compacted in-situ using small scale standard compaction equipment
Low-alkalinity, High-Performance Concrete	The composition varies to suit the specific application.	Poured in place as an structural component of sealing systems or as a working surface, adjacent to sealing systems components
Asphalt mix	Mix of asphalt and filler	Poured in place as an alternative low-permeability seal material with some self-sealing capacity.
Conventional structural concrete	Sulphate-resistant Portland cement with aggregate	Poured in place.
Other Material Combinations	For example: mixtures of highly compacted pellets of mixed composition and fine clay-based materials	The placement method varies depending on the material and the specific application.

Between 2006 and 2009, NWMO conducted several studies to assess the properties of bentonite-based sealing materials. The focus of several of these studies was on the effect of saline porewater on sealing material characteristics and on microbial viability, as discussed in Section 5.1.1.1. The tests included a consolidation and triaxial laboratory testing program.

Baumgartner et al. (2008) completed one dimensional (1D)-consolidation tests using $CaCl_2$ solutions at salinities up to 100 g/L in during the initial stages of development of a sealing materials behaviour database. In conducting these tests it was observed that the behaviour of the clay-based sealing materials was dependent of the salinity of the water used for specimen preparation. Several tests were conducted (Priyanto et al., 2008a, b) to investigate the effect of salinities up to 250 g/L on the behaviour of HCB, DBF and LBF using 1D-consolidation tests. In a limited number of those tests it was found that similar specimens prepared with 250 g/L NaCl had a higher hydraulic conductivity than specimens prepared with 250 g/L $CaCl_2$, and that for a similar salt concentration of 250 g/L, the NaCl solution reduced swelling pressure of the HCB specimen more than the $CaCl_2$ solution.

In the first phase of triaxial testing, the program investigated the behaviour of LBF and DBF saturated with distilled deaired water (Blatz et al. 2008). The results of these tests provided the isotropic consolidation and stress-strain properties of LBF and DBF materials under saturated conditions, which are required parameters for numerical simulation of the behaviour of these materials. The test results allowed the interpretation of both strength and stiffness parameters (i.e., Bulk Modulus and Young’s modulus) providing parameters for use in numerical models.

In addition to the consolidation tests, triaxial tests and microbial viability test programs, NWMO has also contributed to the Backfill and Closure (BACLO) project. This work was conducted as part of a multi-party (SKB, Posiva and NWMO) study on piping, erosion and backfill stability done in several laboratories and at the Äspö Hard Rock Laboratory in Sweden. Tests were conducted to assess the manner in which water is taken up and transported through an assembly of compacted clay blocks and bentonite pellets configured to represent the backfill in a repository room. A schematic of the testing apparatus is illustrated in Figure 5.3. Results showed that the erosion rate was affected by the inflow rates and the initial condition of the tests.

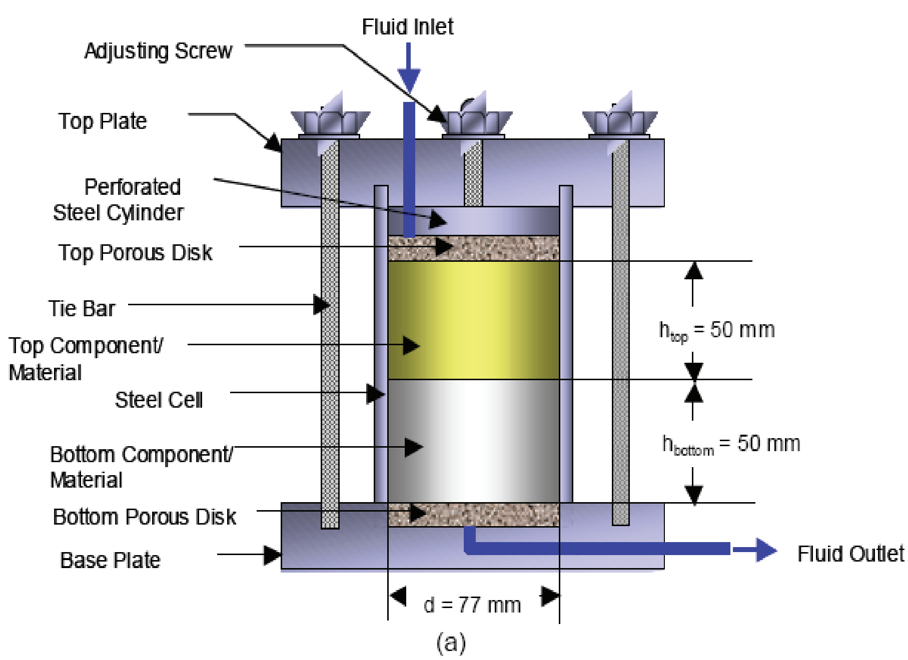

Figure 5.3: Illustration of the laboratory-scale sealing material testing apparatus used in the BACLO project.

A report documenting the thermal, hydraulic and mechanical (T-H-M) properties of repository sealing materials, that expands on the information provided in Baumgartner (2006), was issued in 2009 (Man and Martino 2009). The report included a set of definitions, characteristics and thermal-hydro-mechanical (THM) properties of sealing materials that will be useful for defining future technical specifications, analyses and engineering studies for a repository design.

Rationale for Future Work

The behaviour of sealing systems for a repository constructed in sedimentary rock needs to be evaluated under the expected repository conditions. Recent experimental work conducted has demonstrated that the salinity of the water present in the geological media as well as the composition of the water used for preparation of sealing materials can have an impact on the performance of the sealing components. Testing of bentonite-based materials to be used in a repository is needed to fully characterize their behaviour under repository conditions.

Work Program B

NWMO initiated a consolidation and triaxial testing program to characterize the mechanical properties of the proposed design of bentonite shaft seal materials in the highly saline conditions (200 to 300 g/L mixed Ca/Na-Cl) of the groundwater in Ordovician sedimentary rock, as well as in fresh water conditions. NWMO is planning to continue consolidation tests on HCB, DBF and LBF materials to characterize their behaviour under compression in highly saline groundwaters to support repository design development. Triaxial compression tests on DBF and LBF materials are also planned.

NWMO is planning further studies with international partners on the development and optimization of methods for filling the gaps in the sealing materials for both the in-floor borehole and the horizontal tunnel container placement methods. This study would include the influence of bentonite pellet shape, size and particle size distribution.

Work is also planned to characterize the properties of the 70/30 bentonite/sand mixture being considered as a reference shaft seal material. These will include porosity, diffusivity, hydraulic permeability and gas permeability, as well as swelling and basic mechanical properties. Long-term durability and compatibility with concrete and with potential host rocks will need to be studied either with appropriate models or experiments.

5.2.2 Concrete-Based Seals

Concrete is being considered for use a sealing system component in a number of national deep geological repository concepts for used nuclear fuel. Cement-based grouts may also be used in these areas for fracture filling and to mitigate the effects of the excavation damage zone in the rock. Concrete may also be used as cap seal for shafts or ramps, as tunnel support and/or to provide a floor/work surface for access tunnels and placement rooms. Concrete with different compositions and properties are required for each application.

State of Knowledge

A high pH leachate from the concrete used in a repository could have a negative effect on the swelling characteristics of bentonite and other clays used in repository seals. A performance concrete such as the low-heat high-performance concrete (Gray and Shenton 1998) has a pH in the range of 9 to 10, which is lower than a regular Portland cement (pH ~12). The lower alkalinity lower pH of leachate from this concrete reduces the potential for a detrimental effect on the swelling ability of clays.

Rationale for Future Work

Martino (2006) assessed the issues affecting the durability of concrete in a deep geological repository and identified areas that require further investigation, such as the long-term behaviour of low alkalinity concrete and structural concrete at elevated temperature in high-salinity and elevated-sulphate groundwater. The transport properties of structural concrete and low-heat high-performance concrete need to be measured under specific repository conditions.

Work Program **B**

NWMO intends monitor developments in the long-term performance of concrete and other sealing materials by participation in international sealing demonstration projects such as the Enhanced Sealing Project being conducted in cooperation with other national radioactive waste management organizations. Work is also planned to characterize the transport properties of a low-heat high-performance concrete formulation being considered as a reference shaft seal material. These will include porosity, diffusivity, hydraulic permeability and gas permeability, as well as basic mechanical properties. Long-term durability and compatibility with bentonite-sand and with potential host rocks will be studied via modelling and experimental work.

5.2.3 Asphalt-Based Seals

Asphalt-based shaft seals are being studied as an alternative shaft seal material that can provide redundancy in long-term seal performance due to their different chemical nature from clay and concrete-based seals. However, there is less information available on these potential seals than on bentonite-sand based seals.

Work Program **B**

The transport properties of a reference asphalt seal mixture needs to be measured. These include porosity, diffusivity, hydraulic permeability and gas permeability. Long-term durability and compatibility with bentonite-sand and with potential host rocks will need to be studied either with appropriate models or experiments.

5.2.4 Sealing Materials Demonstration Projects

The Enhanced Sealing Project

AECL's Underground Research Laboratory (URL) in Manitoba is being decommissioned. Part of the decommissioning activities included the placement of composite seals consisting of concrete and clay components at the intersection of the URL access shaft and ventilation shaft with Fracture Zone 2 (FZ2). The purpose of these seals is to isolate the near-surface groundwater flow systems from deeper, saline groundwater (Dixon et al, 2009). The location of the shaft seals is shown in Figure 5.4.

NWMO is participating with ANDRA (France), Posiva (Finland), SKB (Sweden) and AECL (Canada) in a multi-year project that consists of instrumenting and monitoring the composite concrete- bentonite seal placed in the access shaft of the URL. The work is being conducted by AECL with support from the four partner organizations.

The installed access shaft seal consists of a lower, reinforced low-heat high-performance concrete component designed to act as structural support, a 40/60 clay-sand mixture component of approximately 5 m diameter and 6 m in length (compacted on site), and an upper concrete component that would restrict expansion of the clay component and result in the development of a swelling pressure of approximately 2 MPa.

A full description of the seal construction and instrumentation array is given by Dixon et al. (2009). The ESP instrumentation includes a suite of 66 instruments that monitor 95 seal parameters, including strain, temperature and hydraulic pressure in the concrete components, and water content, pore pressure, total pressure and temperature in the clay component. Total displacement is also monitored at the top of the upper concrete component. Two other reports prepared by AECL complete the documentation of the seal construction and provide initial monitoring results (Martino and Kaatz 2010, Martino et al. 2011).

The major remaining task in the project is the continued collection and interpretation of data. Monitoring results reported in 2010 indicated that the seal components are behaving as predicted. Monitoring of the seal evolution is planned to continue until 2013 when the results will be evaluated and further extension of the monitoring period will be considered.

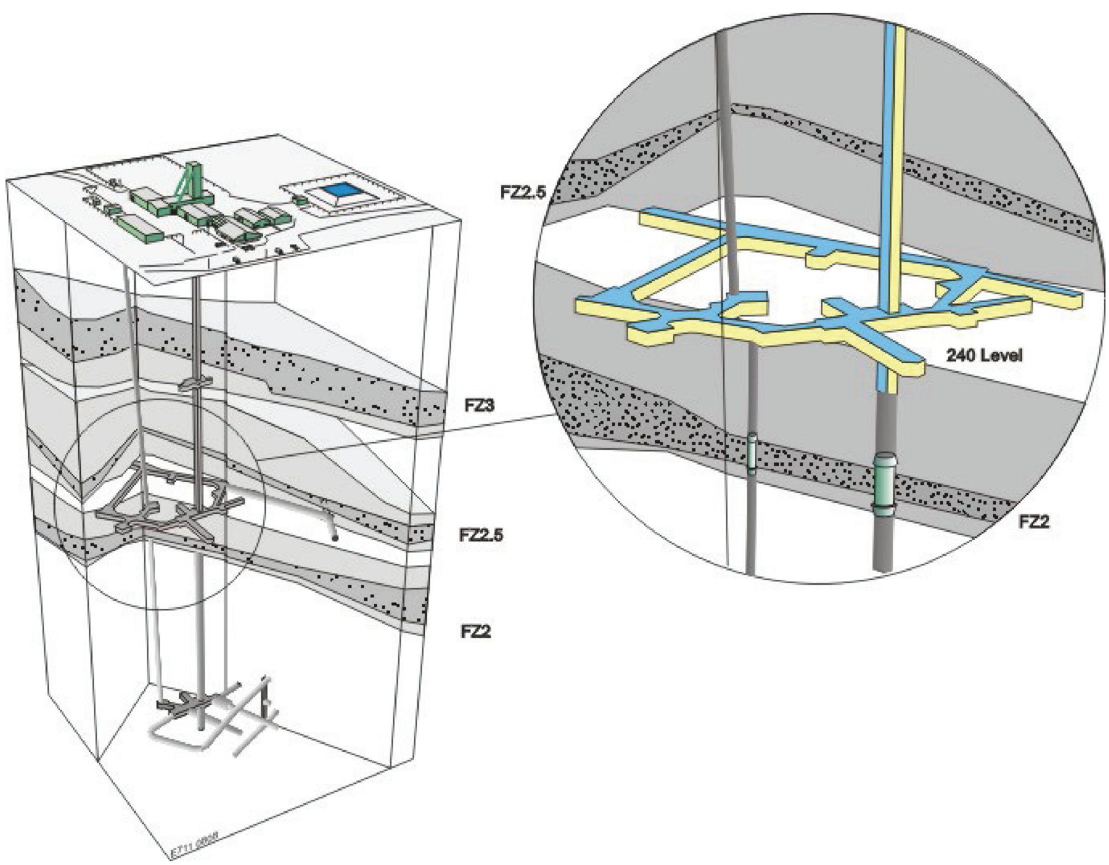

Figure 5.4: Location of the URL Shaft Seals at Fracture Zone 2. The ventilation shaft seal is on the left and the access shaft seal is on the right side. The seals were installed approximately 30m below the experiment tunnels at the 240 Level.

6 GEOSPHERE

The main objectives of the geosphere work program are to: (1) Develop and update geoscientific criteria for the evaluation of potential candidate repository sites; (2) Develop plans and methods for conducting preliminary and detailed geoscientific site evaluations in crystalline and sedimentary settings; and (3) Advance the understanding of geosphere stability and its resilience to long-term perturbations. This is achieved through a multidisciplinary approach involving the coordinated effort of research groups drawn from Canadian universities, consultants, federal organizations and international research institutions. In particular, the NWMO geosciences program is participating in the Äspö Modelling Taskforce, the Greenland Analogue Project and the Mont Terri Underground Rock Laboratory Project.

NWMO staff continues to acquire field investigation experience relevant to a used fuel deep geological repository from their involvement in Ontario Power Generation's Low and Intermediate Level Waste Deep Geological Repository Project. This includes the planning and execution of detailed site characterization activities, collection, management and integration of geoscientific data and quality assurance processes.

6.1 SITE EVALUATION PLANS AND METHODS

In 2010, the NWMO published "*Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel*" (NWMO, 2010). The process includes a list of site evaluation criteria and a site evaluation process. It is anticipated that the suitability of potential candidate sites to safely host a deep geological repository will be evaluated over several years in a stepwise approach. Each step is designed to evaluate the site in increasing degree of detail as follows:

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

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

3. Detailed field investigations to confirm suitability of one or more sites based on detailed site evaluation criteria. Field investigations would include airborne and surface-based geophysical surveys, characterization of the existing environment, drilling and monitoring of boreholes, field and laboratory testing and monitoring activities.

6.1.1 Site Evaluation Criteria

The site selection document lists a set of initial criteria to support site screenings and a list of more detailed criteria to support feasibility studies and detailed site characterizations. The initial screening criteria states that the site must have enough available land to accommodate the repository surface and underground facilities, and that this land must be outside of protected areas, heritage sites, provincial parks and national parks. It also states that the available land must not contain groundwater resources or economically exploitable natural resources at the repository depth, so that the repository site is unlikely to be disturbed by future generations. The more detailed geoscientific evaluation criteria include a wide range of factors that a site needs to meet in order to fulfill the five following safety functions:

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

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

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

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

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

6.1.2 Generic Approach for Implementing Initial Technical Site Evaluation

NWMO has developed plans for conducting initial screenings and feasibility studies. The plans describe how the initial screening and detailed criteria is to be applied, the data requirements to conduct evaluations, the nature and extent of the preliminary field studies that may be carried out during the feasibility studies, and propose possible approaches that could be used to assess larger areas versus specific sites.

The outcome of this work program will be used as a basis for discussion with interested communities and the development of procedures for site-specific geoscientific evaluations.

6.1.3 Background Geoscientific Information

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

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

6.1.4 Review of Geophysical Site Characterization Methods

State of Knowledge

Airborne and surface-based, non-intrusive geophysical methods may be used to assess rapidly and cost-effectively numerous geoscientific characteristics of interest to a range of disciplines (including the geological, hydrogeological, hydrochemical, geotechnical, transport and biosphere properties models). Geophysical methods and remote sensing have been an integral part of the geosphere characterization in all repository studies in both crystalline and sedimentary rock. Many satellite, surface and airborne techniques have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development and the available technology at the time.

A state-of-the-science review on available satellite, airborne and surface-based, non-intrusive geophysical site characterization tools and methods that could be used during the initial stages of the siting process was completed (Emsley et al., 2008; Table 6.1). This review summarized recent technological advances in this area, allowing the NWMO to make informed decisions when selecting the tools and methods for conducting initial site evaluations. The review addressed a number of aspects including the geoscientific characteristics that could be assessed by various methods, their accuracy, limitations and constraints, applicability to sedimentary and crystalline formations, commercial availability in Canada, survey time scales, strengths and weaknesses of each method, etc. The study also included a review of key elements to be considered during survey design and also the geophysical methods and techniques that have been used in similar site characterisation programs in other countries.

Also, in order to develop readiness for detailed site characterization, a report reviewing available borehole-based geophysical tools and techniques for characterizing repository candidate sites was prepared (Monier-Williams et al., 2009; Table 6.1). The report evaluates borehole methods and focuses on state-of-the-science technologies, their applicability, accuracy, limitations and constraints, and best practices. Nine studies were discussed, including both crystalline and sedimentary rock environments, in Europe and North America. The project sites presented include nuclear repository sites, underground research sites and heavy civil works. The techniques considered include: wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and nuclear magnetic resonance logs); flow logging tools (impeller, heat pulse, electromagnetic, and fluid tracking); seismic methods (sonic and full waveform, tomography, reflection and vertical seismic profile surveys); borehole radar; and borehole time domain electromagnetic surveys and cross-hole electromagnetic surveys. The report provides guidance on the benefits and constraints associated with specific techniques. In addition, typical borehole geophysical applications were reviewed, including the determination of lithology and stratigraphy, physical properties, rock structure, hydrogeologic properties, as well as in situ stress investigations and well inspections.

Work Program C

The review indicated that geophysical methods are well established and ready to be applied to characterize potential sites. No additional research and development of methods is currently planned.

Table 6.1: Geophysical Methods Reviewed

Type	Method
Satellite Surveys	• High resolution satellite imagery • Synthetic Aperture Radar Interferometry (InSAR) • Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER)
Airborne Surveys	• Aerial photography • Digital terrain mapping (Radar, LiDAR) • Hyperspectral imaging • Magnetics • Radiometrics • Electromagnetics • Gravity
Deep Ground-Based Surveys	• Seismic reflection (2D and 3D) • Gravity • Electromagnetics • Magnetics
Shallow Ground-Based Surveys	• Seismic refraction • Electrical resistivity imaging (ERI) • Ground penetrating radar (GPR) • Frequency domain electromagnetics (FDEM) • Spontaneous potential (SP) • Induced polarization (IP)
Borehole Methods	• Borehole orientation • Normal electric • Induction • Natural gamma • Spectral gamma • Density • Neutron • Caliper • Optical televiewer • Acoustic televiewer • Nuclear Magnetic Resonance (NMR) • Fluid temperature and resistivity • Impeller flow meter • Heat pulse flow meter • Electromagnetic flow meter • Full waveform sonic • Vertical Seismic Profile (VSP) • Cross-hole seismic reflection • Borehole radar • Borehole TDEM • Cross-hole EM

6.1.5 Seismicity

The seismic design of a deep geological repository is similar to that of underground structures such as deep tunnels and mine openings with the exception of the longer earthquake return periods that need to be considered for a repository. Seismic response of underground structures is distinct from the response of most surface structures because of their complete enclosure in the host rock. Field observations have shown that underground structures suffer appreciably less damage than surface structures and deep tunnels are safer and less vulnerable to earthquakes than shallow tunnels (Hashash et al. 2001). The seismic design of a repository requires an understanding of the anticipated ground shaking at repository depth as well as an evaluation of the response of the host rock and repository components to such ground motion. The design approach consists of three main steps:

1. Seismic Hazard Assessment for the prediction of the seismic risk and environment at the site;

2. Evaluation of the geosphere response to ground shaking at depths; and

3. Assessment of the structural response of the repository components to ground shaking.

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

So far, geoscience work programs related to seismicity focused on developing methodologies for Seismic Hazard Assessment in low seismicity areas, which is a challenging task because of the long timeframes that are considered for deep geological repositories (>100,000 years). Other areas pursued include understanding attenuation of seismic ground motion with depth and supporting seismic monitoring conducted within the Canadian Hazards Information Service of Natural Resources Canada.

The following sections provide an overview of the various work programs that the NWMO is pursuing to develop readiness for conducting seismic hazard assessment studies at potential candidate sites.

6.1.5.1 Seismic Hazard Assessment in Low Seismicity Areas

State of Knowledge

While the Canadian territory contains large seismically stable areas (stable craton cores), accurate prediction of the long-term seismic hazard in such areas is challenging because of the lack of seismic data records and the long-timeframes involved (>100,000 years). Studies in other low-seismicity areas around the world suggest that these areas are capable of producing large (>M6) low probability earthquakes (Johnston et al., 1994). Using seismic data from other stable cratons around the world, Fenton and Adams (1997) constrained the maximum earthquake magnitude in the Canadian stable craton to M7. Also, Fenton et al (2006) suggested that Northern Ontario may have experienced 20 to 40 earthquakes larger than M6 during the last 10,000 years. This suggestion may, however, not be fully accurate as it is partly based on seismic data from other world stable cratons that do not all have comparable geological and tectonic settings as Northern Ontario (Atkinson and Martens, 2007).

Seismic Hazard Assessments can be conducted by means of deterministic and/or probabilistic approaches. Deterministic Seismic Hazard Assessment (DSHA) considers the largest believable or credible earthquake that can occur at any given seismic source. While DSHA provides a straightforward framework for the evaluation of worst-case scenarios at a site, it provides no information about the likelihood and frequency of occurrence of the earthquake. If such information is required, a Probabilistic Seismic Hazard Assessment (PSHA) should be undertaken. PSHA provides a framework in which uncertainties in the size, location and recurrence rate of earthquakes can be identified, quantified and combined in a rationale manner. In areas where no active faults can be readily identified it may be necessary to rely on a purely statistical analysis of historic earthquakes in a given region, which is a challenge for low seismicity areas.

Work Program **B**

In 2009 NWMO initiated a state-of-the-science review of existing seismic hazard assessment approaches for low seismicity regions. The review is on-going and will evaluate the validity of the underlying assumptions associated with seismic approaches in stable cratonic regions and will attempt to identify the different physical processes of stress-strain regimes and release mechanisms that characterize active versus stable continental regions. The outcome of the review will form the basis for developing a Seismic Hazard Assessment Methodology that could be applied to predict the seismic risk and environment at potential candidate sites.

6.1.5.2 Seismic Monitoring

State of Knowledge and Work Program

NWMO continues to support seismic monitoring activities conducted by the Canadian Hazards Information Service (CHIS) of Natural Resources Canada in low seismicity areas of the northern Ontario and eastern Manitoba portions of the Canadian Shield. The continuing objective of this 29 year-old program is to observe and document low levels of background seismicity in the Canadian Shield, using approximately 18 seismograph stations in the study area. The monitoring results are reported annually and used to update magnitude-recurrence curves. For example, 114 seismic events were recorded in 2008 (Figure 6.1). The monitoring results are summarized in Hayek et al. (2009).

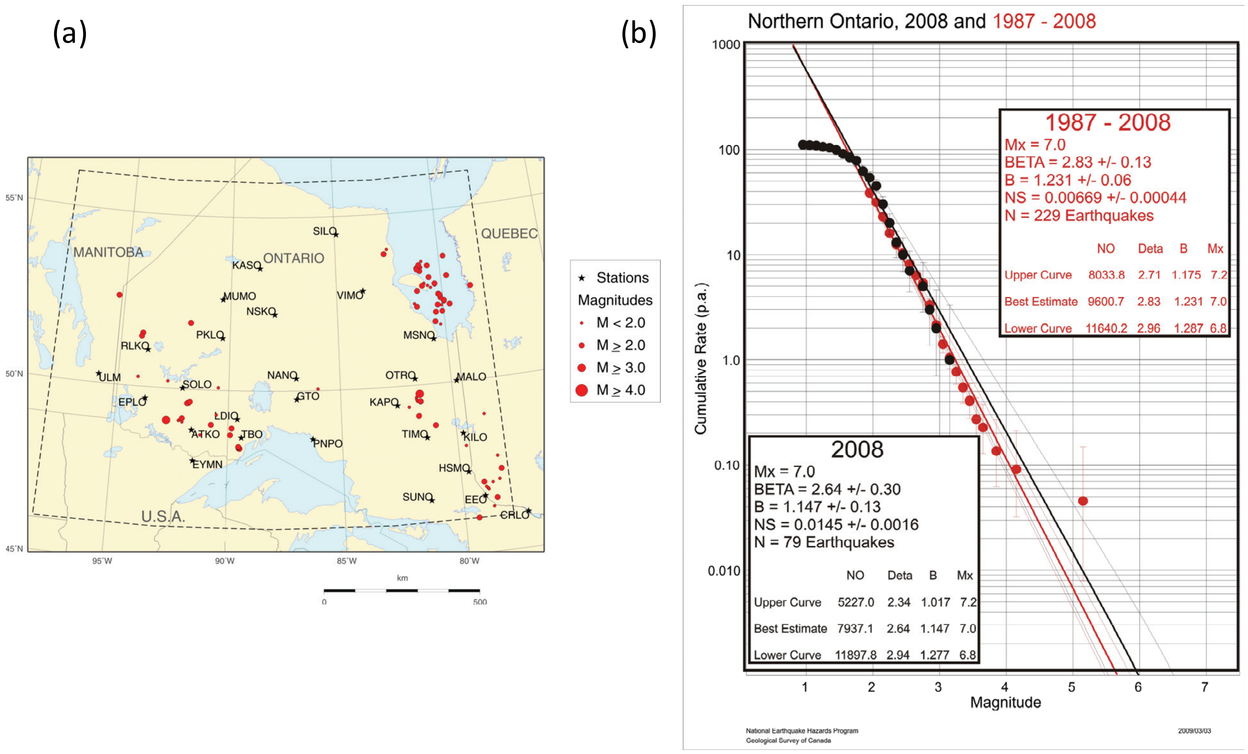

Figure 6.1: (a) 2008 Seismic events in Northern Ontario and adjacent areas. (b) Recurrence curves for Northern Ontario (Hayek et al, 2009).

Work Program

B

It is anticipated that NWMO effort in the area of seismic monitoring will become more site specific once potential candidate sites are identified in willing host communities.

6.1.5.3 Paleoseismology

State of Knowledge and Work Program

Seismic Hazard Assessment can be enhanced through paleoseismology studies. These studies can provide detailed information on past tectonic features and events. However, their application to stable cratons in North America may be difficult as the rate of deformation (e.g. fault slip rate) away from tectonic plate margins are very low compared to erosion and other long-term geomorphologic processes. Despite this deficiency, it is recognized that paleoseismology studies should not be ignored in Seismic Hazard Assessment.

Paleoseismology is the interpretation of past seismic events via the examination of sedimentary deposits formed after fault ruptures, or those disturbed by ground shaking. Paleoseismology, as an interdisciplinary field of research, utilizes concepts from Quaternary geology together with seismology, structural geology and tectonics to enhance our knowledge of past seismicity in an area. The primary focus of paleoseismology is its effects on Quaternary age deposits and land forms. In Canada, quaternary deposits form most of the overburden. Most of the glacial sediments in Canada were deposited during the Late Wisconsinan when the Laurentide ice sheet reached its maximum about 20,000 years ago. Detectable features of paleoseismic disturbance that may have occurred in these sediments during and after this period will provide knowledge relevant to the assessment of regional seismic risk.

A state-of-the-science review was conducted on the applicability of paleoseismology methods to the geological settings typical of the four nuclear provinces to assess whether traditional seismic hazard assessment methods could be complemented by paleoseismology studies (Sims, 2010). The review presents an update of methods and material published in J.P. McCalpin's book "Paleoseismology" in 1996 and assesses their applicability to typical central and eastern Canadian sedimentary and crystalline rocks for the purpose of siting and designing a deep geological repository.

The review also examines the use of geological features such as liquefiable sediments, paleolacustrine deposits, and submarine sedimentary structures in modern lakes, speleothems and surface travertine, precarious rocks and surface post glacial faulting to extract seismological information and extend the seismic record. After compiling and reviewing geological and seismological literature and maps for all four provinces it was concluded that reconnaissance of seismic induced deformation in lacustrine varved deposits and liquefaction features in river and stream banks could provide opportunities for gathering additional information on past unknown moderate to large earthquake events.

Rationale for Future Work

It is anticipated that NWMO's effort in the area of paleoseismology will need to become site specific once potential candidate sites are identified in willing host communities. Therefore, a more focused effort in this area will be required in support of the siting process.

6.1.5.4 Seismic Response of an Underground Facility

State of Knowledge

The seismic response of an underground structure, such as a deep geological repository is a function of the ground motion characteristics that develop at depth following a seismic event. Evidence and case histories show that ground motion at depth is less severe than that measured at the surface (EPRI 1994) and that underground structures are less susceptible to damage during an earthquake (Power et al. 1998). However, because there is a lack of actual subsurface motion data, current seismic design practices are based on ground motion characteristics measured at the surface and do not consider attenuation with depth, which could lead to an overestimation of the seismic loading.

In late 2006, NWMO initiated a multiphase seismological study with Dr. Gail Atkinson of Carleton University/University of Western Ontario to quantify the variation of seismic ground motion response with depth using field measurements at the Sudbury Neutrino Observatory (SNO), which is located beneath the Inco Creighton Mine in Sudbury, Ontario. Five three-component, broad-band oriented seismographs were installed at different depths: two units at surface level, one unit at the 4600 ft level and two units at the 6800 ft level. Their location is illustrated in Figure 6.2. The experiment, called PUPS POLARIS, quantified the reduction of seismic ground motion, with respect to surface ground motion, at various depths. (Atkinson and Kraeva, 2010). The results of the seismic monitoring conducted at these five stations between 2007 and 2009 are illustrated in Figure 6.3 (Atkinson and Kraeva, 2009).

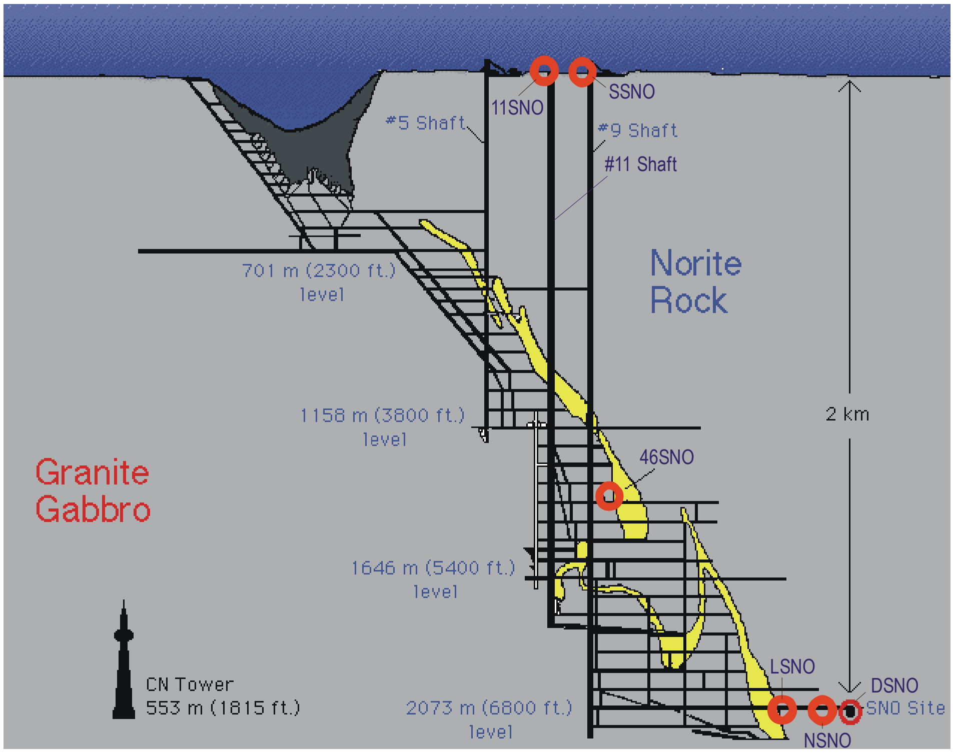

Figure 6.2: SNO Lab and seismograph station locations (SE-NW direction). Approximate positions of stations are shown by the red circles.

In general, earthquake ground motion underground has lower amplitude than that at the surface. The relationship between underground and surface motions is complex, with the ratio of surface/underground motions being a frequency-dependent function that varies with the type of earthquake and the depth of the underground cavern. Motion at the surface is amplified in specific frequency ranges.

For earthquakes at shallow depths, occurring nearby, there are strong surface waves that cause a peak amplification of surface motions relative to those underground, often exceeding a factor of two. These surface waves have frequency near 2 Hz. For larger earthquakes, occurring further away, the surface waves cause amplification at lower frequencies. These motions decrease in amplitude as the depth of the underground station increases. However, at very low frequencies (0.1 Hz) and at very high frequencies (>10 Hz), underground and surface motion have been found to have similar amplitude.

Rationale for Future Work

In general, the comparative behaviour of seismic motion at the surface and at depth at specific frequency range depends on factors such the source depth and distance to the site but also on other factors that are specific of the site geology. These factors should be considered when evaluating the seismic hazard for underground repositories and should be assessed for a specific site in order to predict ground motion levels for specific types of events.

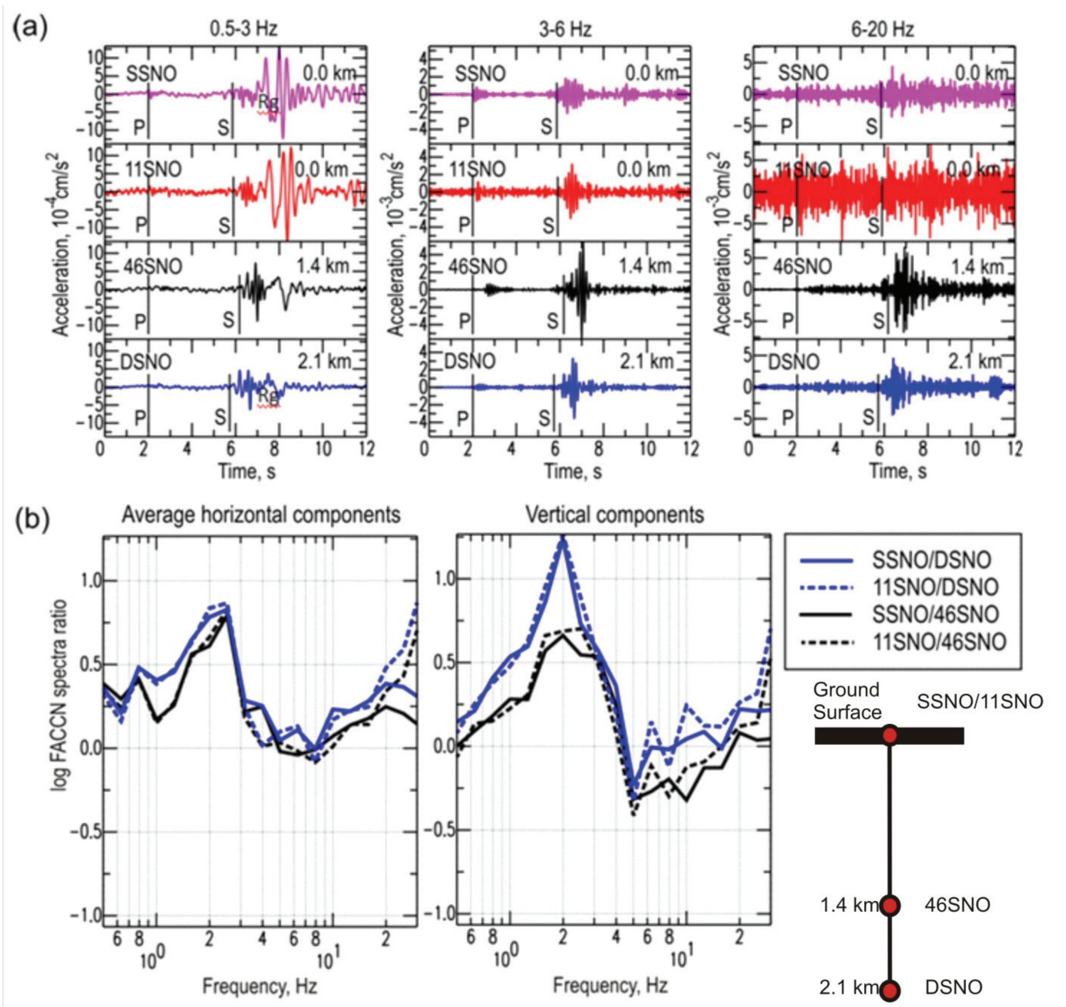

Figure 6.3: The MN2.1 (08/05/2008) mining event 35.3 km from the SNO Lab. (a) shows the amplitude variation as a function of frequency and depth. Vertical components of ground motion acceleration are shown in three frequency bands, 0.2-4 Hz (left), 4-9 Hz (centre) and 9-20 Hz (right). The station names and depths are given above the traces. (b) shows the logarithmic ratios of surface to underground measured amplitudes calculated for the Fourier spectra of the average horizontal component (left) and vertical component (right) of the S-waves. From Atkinson and Kraeva (2009).

Work Program **B**

The underground seismic response study conducted at SNO concluded in 2010. The GSC has compiled and posted a data set of about 200 events recorded from the seismograph stations at the URL, in Pinawa, Manitoba. NWMO will analyze these data to fully characterize the relationship of surface-to-underground ground motions at the URL in both time and frequency domains, and compare these results to those from the SNO experiment.

The focus of the work will then shift to examining the depth attenuation effects at underground sites relevant to the deep geological repository in order to develop site-specific models of seismic wave attenuation as a function of depth.

6.1.6 Matrix Pore Water Characterization

State of Knowledge

Chemical and isotopic (e.g. $\delta^{18}O$, $\delta^{2}H$) compositions of groundwaters and matrix porewaters provide information on the origin and evolution of groundwater flow systems over geologic time frames. Methods to extract matrix porewaters include: crush and leach; out-diffusion of pore fluids into deionized water; ultracentrifugation; vacuum distillation; diffusive exchange; and advective displacement. Each of these techniques has its own benefits and limitations, which are in part dependent on the properties of the rock sample.

In 2005, a collaborative work program was initiated with Gascoyne GeoProjects and the U.S. Geological Survey to develop a protocol for determining the elemental and isotopic composition of pore waters in crystalline rock. Several methods to determine pore fluid composition from freshly drilled cores were investigated and compared, methods, and collecting seepage waters from underground boreholes. Of the methods investigated, the technique of displacing fluids from the core using high speed ultracentrifuge showed particular potential (Gascoyne and Hobbs, 2009). This technique consists in spinning a core fragment at a rate of 15,000 rpm under controlled temperature and pressure conditions to extract pore water from the rock matrix.

Based on the initial success extracting pore water from crystalline rock samples, the program was expanded to study the feasibility of applying the ultracentrifugation method to extract pore water from sedimentary rock. The method was applied to fresh-drilled limestone core from the Bowmanville Quarry in Ontario and initial results demonstrated that it was possible to extract small quantities (<0.5 ml) of pore water from the low porosity limestone samples (Gascoyne and Hobbs, 2009). Neymark et al. (2010) conducted additional studies using the ultracentrifuge technique and demonstrated that most samples with porosities less than about 10 % did not yield any fluid during ultracentrifugation (Figure 6.4). In contrast, all samples with porosities greater than 10% yielded measurable amounts of pore fluid. In addition, compositional and isotopic analyses of fluids extracted using ultracentrifugation showed general agreement to analyses of fluid extracted using leaching and vacuum distillation.

Rationale for Future Work

Evaluation of pore water composition will be an important component of site characterization activities. The compositions of water within the rock matrix (matrix pore waters) of crystalline and sedimentary formations may be similar to those of the groundwaters at the site, but direct information on pore water composition is required during site characterization in order to support this hypothesis. However, extraction of porewater can be difficult, especially for low-permeability sedimentary rocks with low water content. Consequently, a continued effort is required towards establishing appropriate techniques for sampling pore water in both crystalline and sedimentary rock.

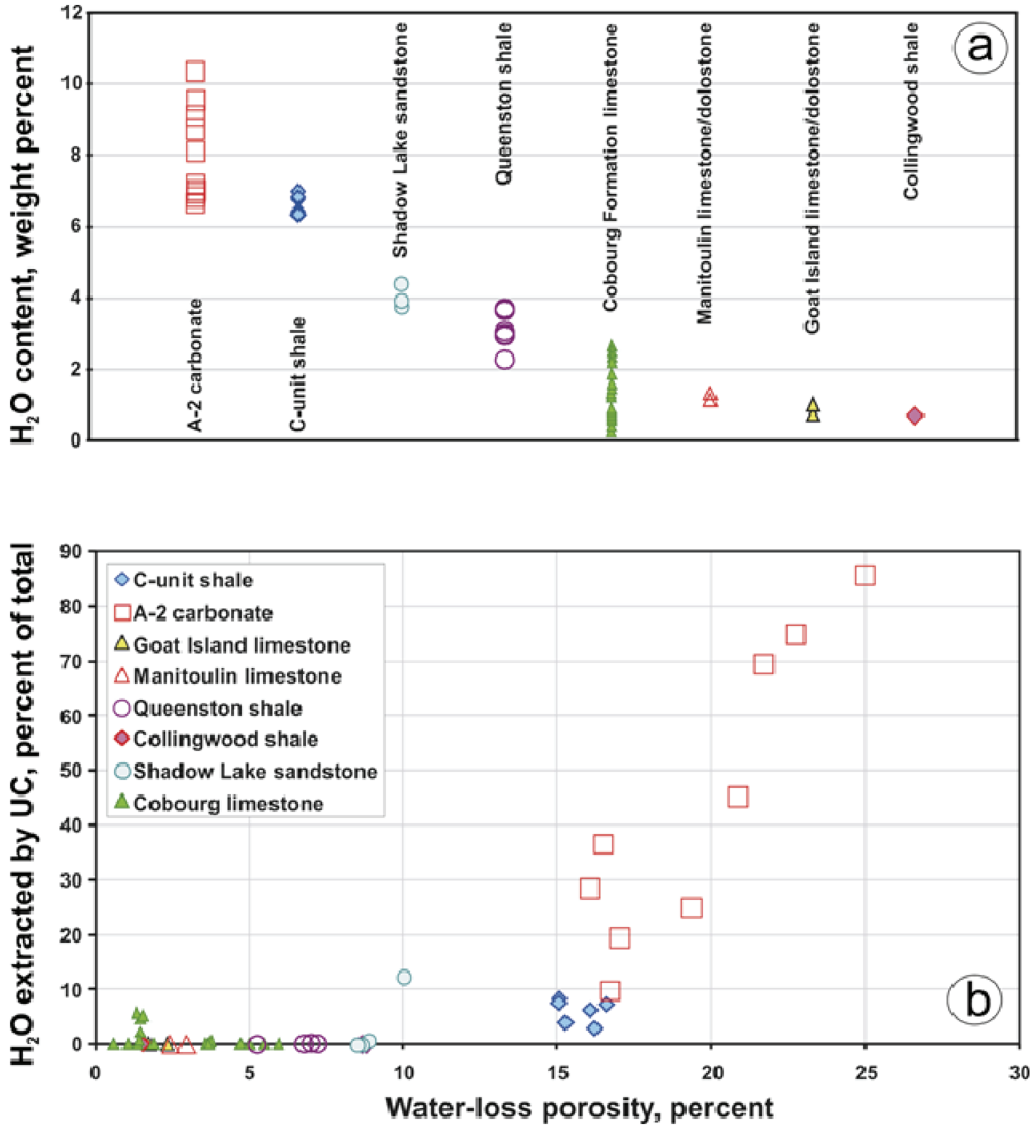

Figure 6.4: (a) Gravimetric total pore-fluid content in different sedimentary rock samples; and (b) plot of water-loss porosity and pore fluid extracted by ultracentrifugation (UC, expressed in percent of total fluid content). Pore-fluid densities of 1.0 g/cm^3 were assumed for samples with no chemical analyses (Neymark et al., 2010).

Work Program **B**

Future research and development on matrix pore water characterization by NWMO will focus on the development and improvement of experimental techniques for extracting porewater from low permeability rock, with particular focus on diffusive exchange and advective displacement methods. Since 2009, NWMO has been collaborating with the University of Bern, Switzerland, to evaluate and benchmark a newly adapted diffusive exchange technique for measuring stable isotope compositions of saline matrix porewaters. In 2011, the work program on matrix porewater extraction will be expanded to evaluate techniques such as vacuum distillation and crush and leach.

6.1.7 Far-Field Microbiology

State of Knowledge

Canadian microbiology research in support of the development for a deep geological repository for used nuclear fuel has evaluated the in situ microbial communities present in crystalline and sedimentary geological environments. Prior to the formation of NWMO, Canadian far-field microbiology research focused on the granitic rocks of the AECL Underground Research Laboratory (Stroes-Gascoyne et al., 2001, and earlier reports cited therein). In 2008, NWMO conducted a preliminary study of microbial communities in potential Canadian sedimentary host rock types with low water content and activity (Stroes-Gascoyne and Hamon, 2008). Phospholipid fatty acid analysis of the samples suggested low to negligible microbial biomass in the samples, consistent with the expectation of low microbial activity in these geological formations that have very low water content and water activity.

Rationale for Future Work

The *in situ* microbiology in the deep subsurface has implications for geochemical conditions, radionuclide migration and gas production. Consequently, many international nuclear waste management agencies, including the Swedish (Hallbeck and Pederson, 2008), Finnish (Pederson, 2008) and U.S. (Meike and Stroes-Gascoyne, 2000), have included microbiology in their site assessments. Microbial communities have the potential to impact variables directly related to repository safety, such as radionuclide migration and corrosion of the used fuel containers, therefore their characterization should be a component of NWMO's site investigation activities.

Work Program **B**

NWMO has initiated a state of knowledge review on far-field microbiology relevant to a deep geological repository for used nuclear fuel. The resulting report will help define the scope of microbial analyses that should be conducted as part of site characterization activities and will identify the experimental work required to support future site investigations.

6.1.8 Assessment of Radionuclide Transport Processes

6.1.8.1 Diffusive Transport

State of Knowledge

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

An X-ray radiographic technique for quantifying the concentration distribution of an iodide tracer solution in rock samples was developed at the University of New Brunswick to study diffusive transport and evolving reactivity in sedimentary rock (sandstone, limestone and shale). This method has the potential to resolve the spatial distribution of porosity and diffusion at a smaller scale than thought possible using through-diffusion techniques, since it allows visualization of the tracer during diffusion, which can be used to detect preferential diffusion pathways and to assess the influence of sample heterogeneity. Since images of the iodine diffusion pattern can be taken at any chosen time intervals, the diffusion coefficient within a sample can be calculated before steady-state is reached. This results not only in shorter measurement times (days to weeks) in comparison to through-diffusion techniques (weeks to months), but also provides details on the sample structure that can be correlated with the diffusion front.

In 2008, a comparison of the through-diffusion method and the X-ray radiography technique was completed. In this study paired samples of archived core of Queenston shale from the Niagara region and Cobourg limestone from the Darlington area in Ontario were examined using both techniques (Cavé et al., 2009). Similar values for the effective diffusion coefficient (De) were obtained using both radiography and through-diffusion methods .

In 2009, a preliminary literature review was conducted to evaluate the diffusive processes that may occur in rock formations. In particular, diffusion processes in heterogeneous sedimentary and crystalline rock with microcrack networks (i.e. cracks at the microscopic level) were examined. Experimental approaches for determining diffusion coefficients were also reviewed, and a preliminary compilation of effective diffusion coefficient values measured in both laboratory and field-scale tracer tests, for a variety of rock types, was prepared. The review indicated that as the scale increases (e.g. from laboratory to field scale), changes in the effective diffusion coefficient may occur due to heterogeneity in the aperture size of the microcracks, size of the matrix (rock) block, the density of the microcracks in the network, the connectivity between the microcracks, and the sorption capacity of the microcrack walls. These preliminary results suggest that further understanding of the impact of scale on diffusion processes is needed to determine the relationship between laboratory-determined diffusion coefficients and in situ, field-scale diffusion.

Rationale for Future Work

Within low permeability geological formations, diffusion is expected to be the dominant solute transport mechanism. To assess the ability of the geosphere to contain and isolate used nuclear fuel in a deep geological repository over relevant time frames (>100,000 years) it is of important to understand the diffusive transport properties of sedimentary and crystalline rocks. Further development of techniques that would enhance our capability to evaluate the diffusive transport properties of low-permeability rock is needed. The recently developed radiographic method to measure effective diffusion coefficients can produce images of the evolution of a tracer as it diffuses through a rock sample is potentially a powerful tool for determining detailed diffusion properties of rock, such as porosity, pore geometry and pore interconnectivity. Additional work is required to further develop the method's capabilities and make use of its potential. Also, since laboratory determination of diffusive properties is usually conducted at a small (cm) scale, a thorough understanding of the scale-dependency of diffusion properties is necessary in order to evaluate the applicability of laboratory-derived diffusion coefficients to scales relevant to a deep geological repository.

Work Program **B**

Over the next few years work will continue in the development of the X-ray radiography method at the University of New Brunswick to enhance NWMO's capability to determine the diffusive transport properties of rock. A similar radiography technique to quantify diffusion-reaction processes using non-conservative tracers (e.g. Cesium) is also being developed over the next several years. In addition, the scale-dependency of diffusion coefficients is being experimentally investigated through the measurement and comparison of laboratory-derived versus in-situ diffusion coefficients on samples from the international Mont Terri Underground Research Laboratory in Switzerland. The scope of the work program, which extends over the next few years also includes investigation of the impact of partial saturation on diffusive transport in low-permeability sedimentary rock.

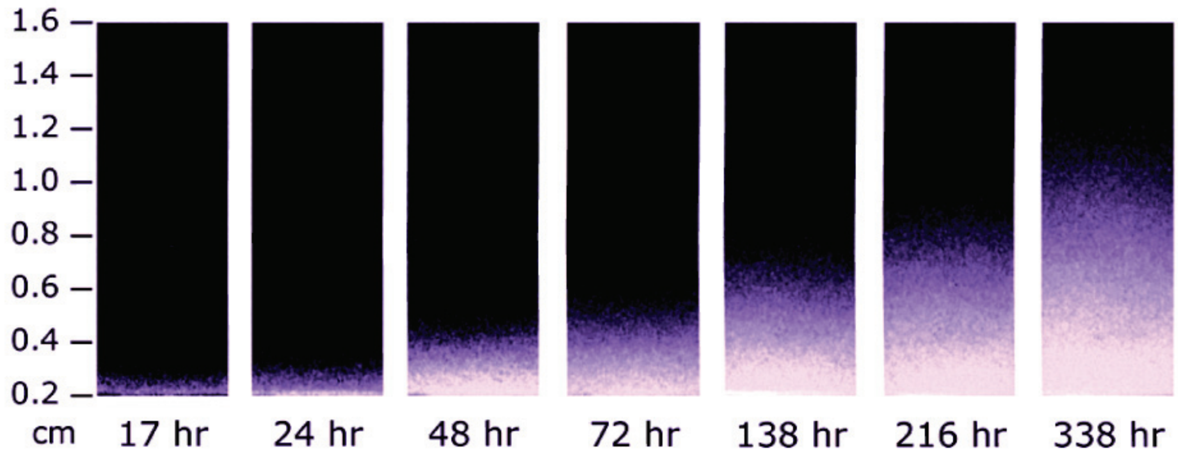

Figure 6.5: Time-series radiographic images showing the transport of Cs through a rock sample.

6.1.8.2 Sorption

State of Knowledge

Sorption plays an important role in regulating the migration of radionuclides through both engineered barriers and the geosphere. There is a considerable database of knowledge developed within Canada and elsewhere on crystalline rock (AECL, 1994, Vilks et al, 2003) and on various clay-based sedimentary rocks.

In Canada, deep geologic conditions are often relatively or highly saline. A review of existing knowledge on methods for understanding and quantifying the sorption properties of rocks in saline waters was conducted in 2008-2009 (Vilks, 2009). The review included the state of knowledge within the Canadian and international nuclear waste management programs on sorption in crystalline rock, sedimentary rock and engineered barrier systems, as well as a broader range of scientific literature on sorption in saline waters and theoretical considerations of sorption processes under saline conditions.

Rationale for Future Work

An understanding of how sorption processes affect mass transport both in the near- and far-field is of benefit to the repository safety case. The state-of-the-science review of sorption in saline waters (Vilks, 2009) revealed a gap in radionuclide sorption data for highly saline conditions such as those found at depth in Canadian sedimentary basins. Although information from existing databases provides valuable knowledge, these databases can only be adapted to high salinity solutions after one has acquired an understanding of sorption processes for the Na-Ca-Cl brines found in Canadian sedimentary and crystalline rocks.

Work Program **B**

On the basis of the recommendations of Vilks (2009), an experimental program on sorption in sedimentary rocks under high salinities was initiated in 2009 that will develop a quantitative understanding of the impact of high TDS (up to ~300 g/L) on sorption and evaluate the effect of high concentrations of Na/Ca ions on sorption processes. The program follows the approach used to establish international sorption databases, and started with experiments conducted using Canadian sedimentary rocks and a range of brine compositions. The work program includes batch experiments to address sorption-specific issues, and dynamic transport experiments designed to relate the sorption processes to mass transport.

6.1.8.3 Colloids

State of Knowledge

The goal of the Colloid Transport Project is to gain insight into the potential effects of erosion of clay-based buffer and backfill materials if dilute water was able to reach the used fuel repository, such as in a glacial melt water intrusion scenario. This experiment was undertaken in collaboration with SKB, in support of their bentonite colloid program, which includes participation in the in-situ Colloid Formation and Migration (CFM) experiment at the Swiss Grimsel Test Site.

In past years, the NWMO has co-funded laboratory scale experiments with SKB to investigate the potential for bentonite colloids originating from repository buffer and backfill materials to facilitate radionuclide transport. The focus of these experiments has been to further the understanding of physical processes that affect colloid mobility, and their results were intended to complement the results of field scale experiments undertaken at the Äspö Hard Rock Laboratory. The laboratory experiments studied the effects of particle size, particle structure, flow velocity, path length and salinity on bentonite colloid transport, and aimed to characterize colloid deposition on fracture surfaces by post-test analysis (Vilks and Miller, 2009 and 2006). The tracer test experiments were performed in the Quarried Block (QB) sample, a 1m x 1m x 0.7m block of granite containing a single, well characterized, variable aperture fracture as shown in Figure 6.6.

Latex spheres, which are almost perfectly spherical, were also used in the experiments for comparison purposes since they provide a useful tool for assessing the effect of particle size on transport. Experiments showed that in dilute water bentonite colloids had a broad size range, from 10 nm to several µm, and that small bentonite colloids (4 to 15 nm) were significantly more mobile than the larger particles. In saline water, bentonite colloids were not transported but Latex colloids were mobile, with migration behaviour influenced by particle size.

In 2008 an experimental plan was developed collaboratively with SKB to use the experience from the QB tests to investigate the mechanisms of bentonite erosion from compacted borehole buffer plugs intersecting a natural fracture and the subsequent transport behaviour of bentonite colloids in the fracture. The experimental plan consisted of first conducting tests in a mock-up, transparent, synthetic fracture, including the preparation and installation of a bentonite plug in a borehole intersecting the fracture. Fluorescent latex colloids were mixed in the bentonite plug to establish whether they could serve as an indicator of bentonite plug erosion.

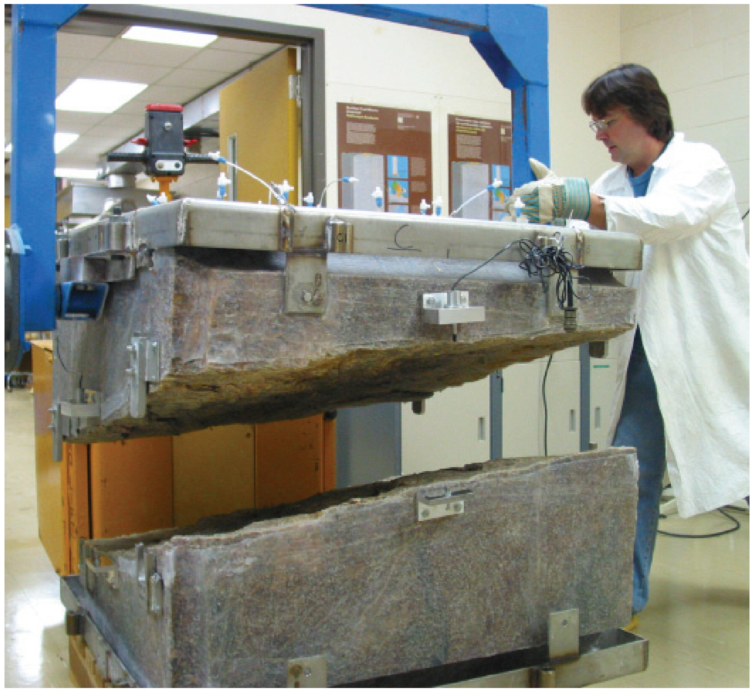

Figure 6.6: Quarried Block sample opened for inspection of fracture surfaces

The mock-up test results established that: i) latex spheres could be used as a marker for bentonite erosion from a compacted plug, as illustrated in Figure 6. 7, ii) mobile bentonite colloid concentrations were significantly less in Grimsel water compared to deionized water, iii) gravitational forces do affect bentonite erosion and transport and, iv) bentonite deposits may alter flow in fractures.

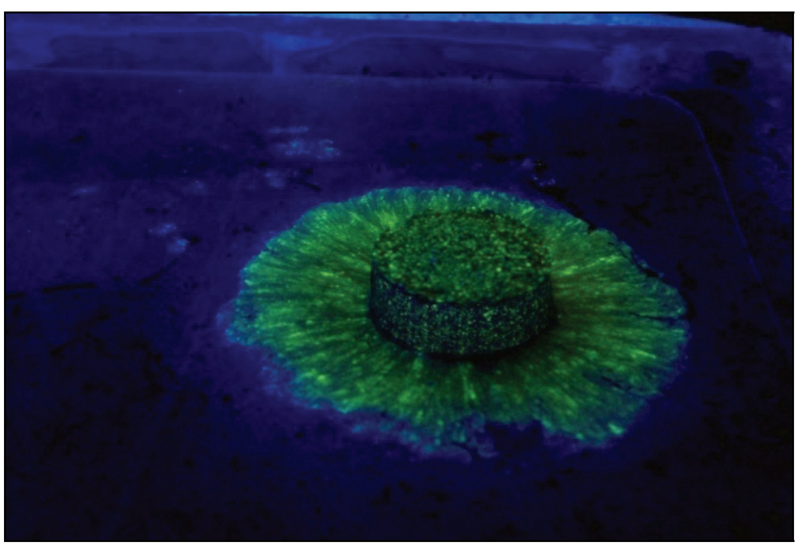

Figure 6.7: Uniform distribution of fluorescent latex spheres within the bentonite visualized during post-test analysis.

In 2009, the experimental plan included the placement of compacted bentonite plugs mixed with latex colloids as a tracer into two large diameter boreholes that intersect the QB fracture. A dipole flow field was imposed across the fracture diagonal at a rate of 44 mL/hr. The erosion and transport behaviour of the bentonite was evaluated by: a) monitoring the evolution of bentonite and latex colloids as water flowed through the fracture, b) conducting solute tracer tests to establish whether the transport characteristics of the fracture had been altered by the bentonite, c) mapping the distribution of suspended bentonite and latex colloids through sampling from a network of intersecting boreholes and, d) opening the QB and directly scanning or sampling the fracture surfaces to map the distribution of retained colloids (Figure 6.8).

Results of the QB tests reported in Vilks and Miller (2010) indicated that in waters containing millimolar amounts of dissolved salts (representative of glacial melt water) the bentonite that expands into an open fracture is likely to form stable deposits that do not release significant concentrations of bentonite colloids. The fraction of bentonite mass loss due to erosion or colloid generation in the presence of Grimsel type groundwater was very small. Although 13 to 14 percent of the bentonite expanded into the fracture in the form of gel deposits, less than 0.15 percent of the original bentonite mass was observed in the form of deposited or transported bentonite colloids.

Work Program **B**

This series of bentonite erosion experiments concluded in 2009 and NWMO research activities in this area concluded in 2010 with the preparation of a summary report on colloid generation and transport in collaboration with SKB.

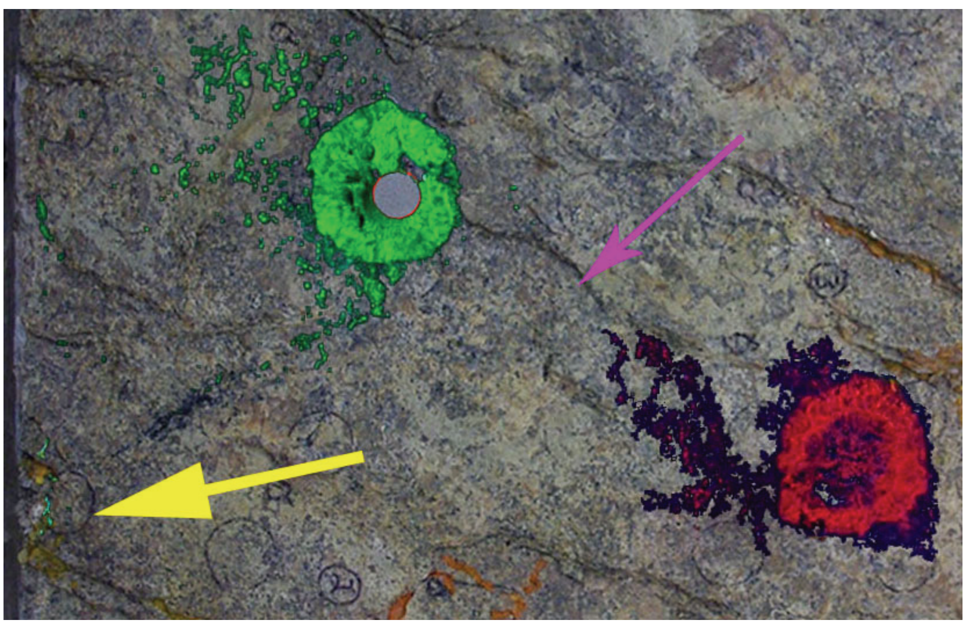

Figure 6.8: Close up of two bentonite plugs with latex fluorescence marking extent of swelling and movement into the fracture superimposed on the bottom fracture surface. The red circle shows original size of bentonite plug (38 mm diameter). Left arrow shows dip direction of fracture plane and right arrow Indicates the approximate flow direction.

6.1.9 Fracture Network Modelling

State of Knowledge

The simulation of fluid flow and mass transport is an important activity for supporting site characterization studies and ultimately the safety case for a deep geological repository. Fracture network models (FNM) can be used to enhance incomplete geological data and to perform sensitivity analyses of groundwater flow and mass transport calculations. In order to accomplish the task of representing fracture geometries, FXSIM3D, a geostatistical tool for probabilistic modelling of complex fracture networks was developed.

FXSIM3D is a research software application developed under Ontario Power Generation's Deep Geological Repository Technology Program (DGRTP) for creating 3D FNMs based on a geostatistical procedure using a wide variety of data on the location and orientation of sub-surface fractures (Srivastava 2002a,b; Srivastava 2006). The types of data acceptable for the FNM code are:

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

The family of FNMs produced by this method are probabilistic in that they consist of equally-likely renditions of the fracture geometry. The FNM generated are realistic and structurally complex, honouring the detail of fracture locations, orientations and other aspects of the fracture geometry, such as the down-dip behaviour of fracture surfaces (Figure 6.9). These models are useful as input to many types of subsequent analyses such as mechanical stability, groundwater flow and contaminant transport, and are also well suited for risk assessment and quantification of uncertainty. In addition, this methodology for creating FNMs is useful at all stages of site characterization as it can provide a framework for guiding field investigation activities with the objective of reducing the inherent uncertainty.

Two different discrete FNM simulations were initially undertaken, the first one for the Whiteshell Research Area (Srivastava, 2002a) and a second one in support of the Sub-regional Shield Flow System case study (Srivastava, 2002b). Subsequently, a third fracture network model based on quarry field data from Lägerdorf, Germany (Srivastava, 2006) was created to verify and validate the modelling procedure.

Rationale for Future Work

In developing a FNM in support of the Sub-regional Shield Flow System case study, the goal was to create geologically and geomechanically sound fracture networks from limited data, such as it might be the case during early site characterization studies. The FNM was included in numerical groundwater models in order to realistically and accurately represent fracture zones.

A fracture network model is considered an essential tool for the development of a geosphere model that can be used for characterization an evaluation of candidate sites. Previously, a version of FXSIM3D was created for each case study. There is a need to develop a quality assured version of the code suitable for use in site feasibility and characterization studies.

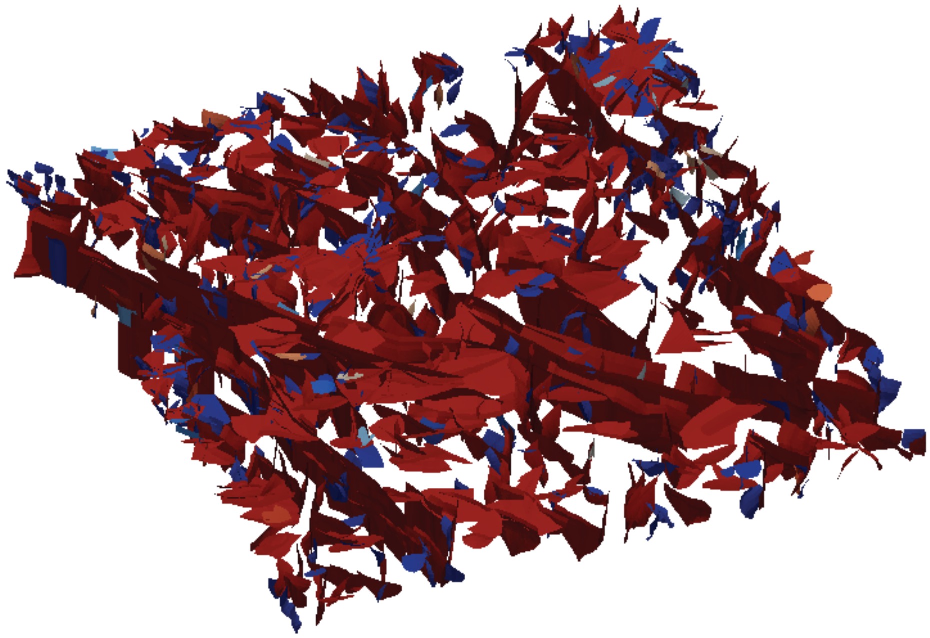

Figure 6.9: Example of a Fracture Network Model generated using FXSIM3D software.

Work Program **B**

NWMO is currently undertaking a project to integrate the previous FNM codes into a single version of the code accompanied by a theory manual, a user manual and verification data sets. Additionally, the NMWO is currently investigating other fracture network modelling codes in order to diversify its capabilities in preparation for site investigations.

6.1.10 Excavation Damage Zone

State of Knowledge

The volume of rock immediately surrounding emplacement rooms, tunnels, shafts and other underground openings that is disturbed during excavation is known as the Excavation Damage Zone (EDZ) and is characterized by structural changes in the rock, such as the formation of microcracks and by significant changes in the rock mass properties, especially those related to flow and transport. The EDZ can be described by means of its geometry, material properties and the time-dependent behaviour of the altered zone. It is highly specific of the rock-type and, as the name suggests, the excavation method is the major contributor to the extent of the damage.

The usual characteristics of the EDZ are that the extent of fracturing around an opening is generally limited to within one tunnel radius of the excavation surface and it is affected by the presence of previous fractures and heterogeneities close to the excavation surface. It is a three-dimensional phenomenon and is related to tunnel geometry and orientation and is loading path dependent.

In all rock types, stress changes due to mechanical and thermal loading contribute to the EDZ development. Stress redistribution processes are well understood and can be readily studied using numerical methods. However, there are data uncertainties in rock mass properties and the in-situ stress state (Posiva 2007, 2006, SKB 2007). In clay-rich rocks, additional complex processes such as changes in moisture content, as well as chemical and biological processes are associated with the EDZ development.

Rationale for Future Work

The actual characteristics and extent of the EDZ depend on the site-specific properties. The available geomechanical models for predicting EDZ parameters are, in some level, capable for providing realistic results. However the predictions are often conservative, therefore more information is needed on the physical parameters of the EDZ in order to improve the predicting capabilities of the numerical tools.

Work Program **B**

A study was initiated in 2009 to review the state-of-the-art in predicting the extent and key material parameters associated with the EDZ around bored and blasted tunnels in sedimentary rocks. Two objectives of the review were to examine the ability of numerical models to simulate the evolution of the EDZ under different excavation sequences and to determine the required extent of shaft cut-off and seal applications (Lanyon, 2011). Both modelling and experimental work is planned in areas identified by the review report, focusing on geological environments of interest to the development of a repository.

6.1.11 Mont Terri Project

NWMO continues its participation as a partner in the international Mont Terri Project in Switzerland. The main goals of the collaborative research project are to: 1) Test and improve techniques for hydrogeological, geochemical and geotechnical investigations in an argillaceous formation; 2) Characterize the Opalinus Clay and its behaviour; and 3) Explore the interactions between the Opalinus Clay and other materials (Figure 6.10). In order to facilitate these goals, a series of experiments are being conducted in boreholes up to 30 m long, drilled in different directions. The Mont Terri Project involves collaboration of international organizations such as NWMO, ANDRA, NAGRA, BGR, CRIEPI, ENRESA, GRS, HSK, IRSN, JAEA, OBAYASHI, SCK-CEN and SWISSTOPO.

Rationale for Future Work

Participation in the Mont Terri Project allows NWMO to gain experience in the analytical and experimental methods being used to actively investigate and characterize clay-rich rocks. The Mont Terri Project also allows NWMO to access to data collected from the Opalinus clay, a potential analogue of sedimentary rock found in Canada and creates a collaborative environment for NWMO to work with other national waste management organizations that are investigating the potential for sedimentary rock to host a deep geologic al repository.

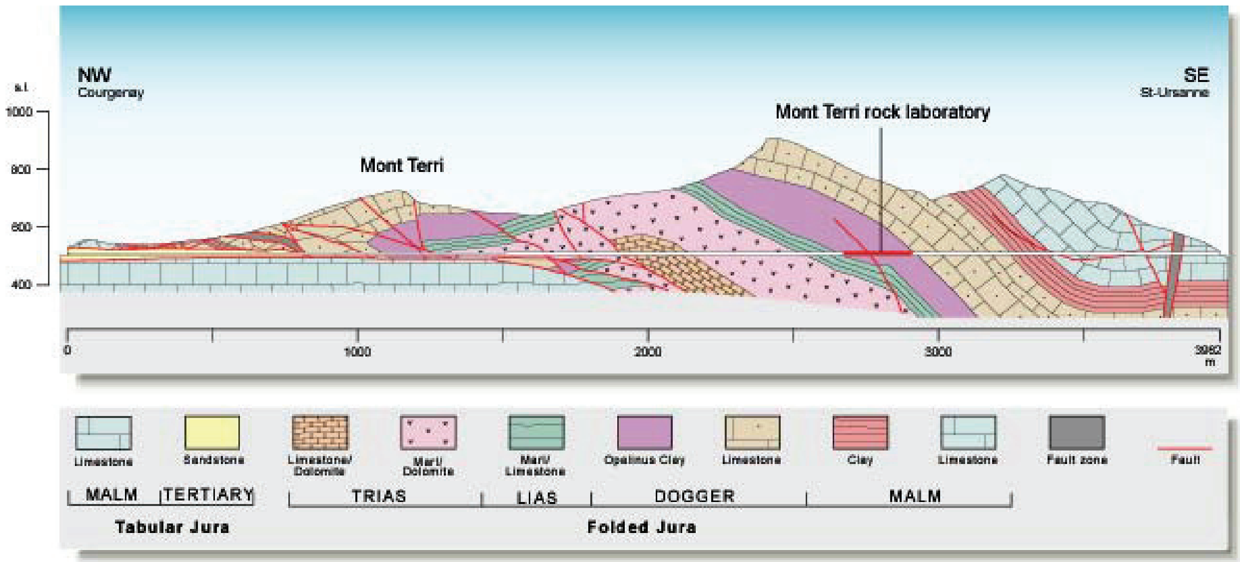

Figure 6.10: Geological cross-section through the Mont Terri anticline indicating the location of the Mont Terri Rock Laboratory. From Hugi et al (2007).

Work Program **B**

NWMO is continuing its involvement in Mont Terri Project and is supporting seven experiments at the laboratory. These are: the DR-A (disturbances, diffusion and retention), DS (determination of stress), HG-A (gas path through host-rock and seals), IC (iron corrosion in Opalinus Clay), LP (long-term monitoring of pore pressures), MA (microbial activity) and MB (mine-by test) experiments.

6.2 LONG TERM GEOSPHERE STABILITY

A major influence affecting long-term geosphere stability within Canada is glaciation.

6.2.1 Surface Boundary Conditions During Glaciation Cycles

State of Knowledge

An essential element in assessing the potential impact of glaciation on a deep geological repository is the ability to adequately predict the surface boundary conditions during glaciation cycles, such as the extent and depth of the permafrost, thickness and kinematics of the ice sheet, ice sheet hydrology, and other attributes. For the purpose of NWMO’s safety case studies including glaciation, these boundary conditions have been predicted using the University of Toronto Glacial Systems Model (GSM) in collaboration with Dr. W.R. Peltier (Peltier, 2006, 2008). The GSM is a statistical model of continental-scale ice sheet evolution. Using this model it is possible to characterize, in a probabilistic manner, the extent to which glacial events may differ from one another. The GSM has been enhanced to enable calibration of the model using a Bayesian methodology, which allows the model to reconcile a large body of observational constraints concerning ice-sheet advance and retreat over the North American continent during the Late Quaternary period of Earth history.

Rationale for Future Work

There are several aspects of the GSM that require further development to improve predictions of glaciation boundary conditions and consequently improve the overall assessment of a repository safety case. One of these is the implementation of better models for the flow of ice over the landscape. This includes the consideration of longitudinal stresses and the interaction of ice streams with the ocean. To facilitate the interaction of glacial ice sheet models with coupled climate models, researchers at the University of Toronto are enhancing the GSM to include unstructured grids. Using unstructured grids allows a finer discretization along the boundaries of the ice sheet model, where the glacial ice streams interact with the ocean. An example of basal topography representation using an unstructured grid is presented in Figure 6.11.

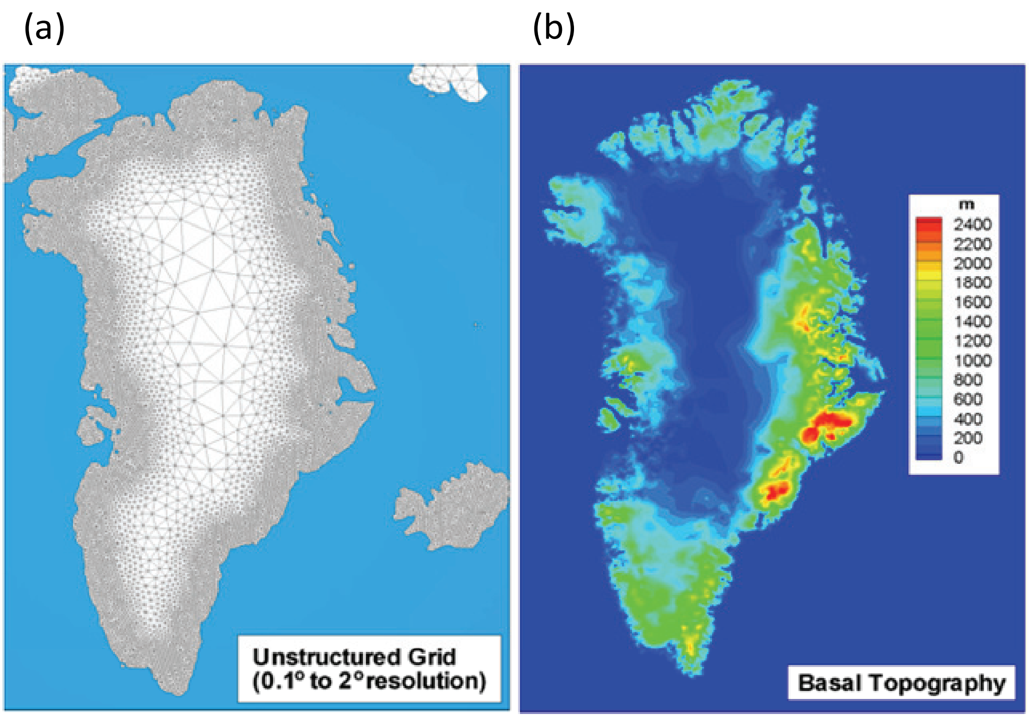

Figure 6.11: (a) Unstructured grid for Greenland Ice Sheet. (b) Basal topography.

Work Program **A**

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

This program investigating boundary conditions during glacial cycles will be continued through to 2014 in order to attain the long-term goals of developing and applying this modelling capability to the safety assessment of future repository designs. The Glacial Systems Model will play an important role in understanding the future geosphere evolution of potential repository sites. This program will continue to enhance the long-term predictive capabilities of the NWMO.

6.2.2 Groundwater Flow and Glaciation

State of Knowledge

A state-of-knowledge review of glaciation impacts on sedimentary rock formations was completed to assess the resilience of deep groundwater flow systems to physical and chemical perturbations at depths and over timeframes of relevance to a deep geological repository.

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

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

The NWMO research and development program on glaciations is ongoing (see Sections 6.2.1, 6.2.3 and 6.2.5).

6.2.3 Reactive Transport Modelling and Glaciation

State of Knowledge

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

Reactive transport modelling (RTM) has been applied using codes such as MIN3P to simulate the long-term evolution of glacial melt water recharge into fractured crystalline rock (Spiessl et al. 2009). A complementary approach has also been used involving the use of transmission electron microscopy (TEM) and paleohydrogeological methods to investigate the presence of weathering signatures in minerals adjacent to crystalline rock fractures to assess the depth of penetration of the oxygen carried by recharging groundwaters in the past (Cavé and Al 2006, Gascoyne et al 2004, McMurry and Ejeckam 2002). Results from such investigations at the Whiteshell Research Area have shown that the depth of penetration of oxygenated, low-salinity groundwaters in the past has been less than 50 m below ground level.

Rationale for Future Work

Mayer and MacQuarrie (2007) established that RTM had not previously been used to assess geochemical processes induced by glaciation in sedimentary rocks. In addition, an evaluation of the applicability of RTM codes to the assessment of water-rock interactions over a range of salinities found that none of the available codes was capable of modelling all the relevant geochemical processes induced by glaciation. It was however noted that modelling studies of seawater ingress and CO_2 sequestration in sedimentary rocks showed promising results, suggesting that modelling of the geochemical evolution in a 2D-subsection of a sedimentary basin is a realistic goal. As a result, during 2008-2009 a version of the MIN3P code was developed that allowed for the coupling of density dependent flow and reactive transport (MIN3P-DENS). Further development of the code is required, however, in order to meet the needs for modelling all the relevant geochemical processes induced by the glaciation and deglaciation cycles in sedimentary basins.

Work Program **B**

Building upon previous NWMO supported work to assess meltwater penetration in fractured crystalline rock using MIN3P reactive transport modelling (Spiessl et al., 2009), work was initiated in 2009 to enhance the capabilities of MIN3P to model transport in sedimentary rocks. A version of the code that allows for the coupling between density dependent flow and reactive transport (MIN3P-DENS) was developed in 2009, and specific formulations for activity coefficients and ionic strength effects (Pitzer equations) were included into MIN3P-DENS (MIN3P-NWMO). The capabilities and limitations of the modified code for simulating regional scale flow and reactive transport in sedimentary basins were evaluated. Reactive transport modelling will be conducted to assess the evolution of fresh water during glacial recharge for larger scale aquifer-aquitard systems in sedimentary basins, where the sedimentary units dip gently inwards from the basin margins (Figure 6.12). Various scenarios representing groundwater flow and reactive transport in sedimentary basins affected by glaciation events will be simulated.

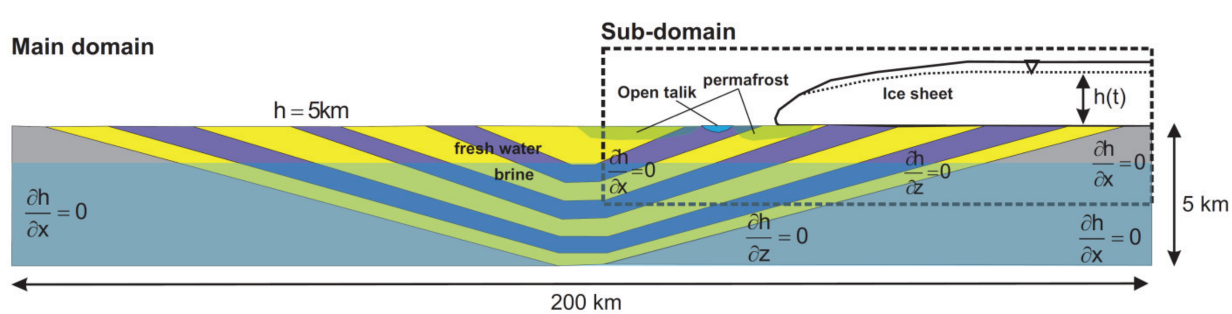

Figure 6.12: Regional conceptual model and potential sub-domain to be used for detailed reactive transport simulations (vertical scale enhancement 5:1).

6.2.4 Glacially Induced Seismicity

State of Knowledge

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

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

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

6.2.5 Greenland Analogue Project

State of Knowledge

Climate induced changes such as the growth of ice sheets and permafrost will alter the ground surface environment and impose a significant perturbation on the geosphere within a time frame that is considered relevant to repository safety. Glaciation impact assessments have to date used simplified models of the ice sheet features and the associated subglacial hydrology in predicted glaciation scenarios. However, development of physical benchmarks is required to support and increase confidence of the analytical predictions. To accomplish this and improve our understanding of how glaciation would affect a repository in the long term, a 4-year (2009-2012) combined field and numerical study called the Greenland Analogue Project (GAP) was initiated by NWMO, SKB and Posiva at the Russell Glacier, located along the western margin of the Greenland ice sheet.

The GAP is divided in three complementary sub-projects:

- Sub-project A involves climate-based energy balance measurements and indirect studies of ice sheet hydrology using ground penetrating radar and ice sheet velocities using differential GPS measurements.

- Sub-project B involves remote sensing of surface conditions in particular supraglacial lakes, as well as direct studies of glacial and sub-glacial hydrology by drilling through to the base of the ice sheet.

- Sub-project C involves borehole drilling to several hundred metres through permafrost and bedrock at several locations ahead of the glacier terminus and instrumenting these boreholes to support data collection for hydrogeological and hydrogeochemical studies.

Following on permafrost studies in the Canadian Arctic (Stotler et al., 2009a, b; Holden et al., 2009) and an introductory field campaign in 2008 near Kangerlussuaq, Greenland, the GAP field program began in 2009 and included the successful initiation of ice sheet and geosphere geochemistry studies. In 2009, research conducted on the surface of the ice sheet included the installation of GPS stations, ground-based radar work, remote sensing of the study area and tracer tests conducted near the ice margin to look at water flow from the surface to the base of the ice sheet. Three boreholes were drilled in front of the ice sheet to investigate the depth of the permafrost in the area and to confirm the presence of a talik beneath a water body (Figure 6.13). Geochemical sampling of surface water bodies was also conducted in 2009 and 2010. Drilling through the ice sheet to the base to investigate temperature and pressure conditions began in 2010, and radar (both helicopter and ground-based) surveys were done over sections of the study area.

Figure 6.13: Drilling of an inclined borehole near a talik lake west of the ice margin as part of the Greenland Analogue Project 2009 field campaign.

Rationale for Future Work

The land based terminus of the glacier is considered a present day analogue of a future glacial environment over both Scandinavia and Canada. Investigation of its hydrology, as well as the hydrogeological and hydrogeochemical processes associated with this portion of an ice sheet will provide a strong scientific basis for assessing the impact of glaciation on the long-term safety of a deep geological repository. The Greenland Analogue Project offers a unique opportunity to investigate these phenomena and advance our understanding of processes associated with glaciation that may have significant impact on the long-term performance of a deep geological repository.

Work Program **A**

Through an extensive field and modelling program, the GAP will evaluate glacial hydrology, groundwater flow and groundwater composition (particularly redox conditions) at the base of a continental-scale ice sheet, and will provide a scientific basis for reducing some of the more significant uncertainties and improving current safety assessment approaches.

In 2009, NWMO and NSERC jointly awarded three Industrial Postgraduate Scholarships to two University of Waterloo Ph.D. candidates and one University of Toronto Ph.D. candidate. These students are conducting research as part of the GAP project, participating in field, laboratory and modelling studies.

6.2.6 Evolution of Deep Groundwater Flow Systems

State of Knowledge

As part of the NWMO Used Fuel Repository Geoscience program, numerical modelling analyses have been undertaken in order to better understand and illustrate groundwater system evolution in both crystalline Canadian Shield rock and sedimentary basin environments during the Quaternary Period (2 million years to present). 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 characterisation data. The numerical methods developed in the execution of these tasks are useful tools to assess and quantify the robustness of site characterization data and to make groundwater flow and transport predictions.

Within the framework of this program, researchers at the University of Waterloo, have used FRAC3DVS-OPG to investigate the factors influencing groundwater system evolution in regional settings. FRAC3DVS-OPG is a numerical code that provides a solution of three-dimensional, density-dependent groundwater flow and solute transport in porous, discretely-fractured media. The current state of knowledge in the modelling of hydrogeological and coupled processes is described below.

In sedimentary basin and crystalline shield environments, the pore-fluids generally become more saline as depth increases. Typically, an increase in the salinity concentration of the groundwater will result in a corresponding increase in density as shown in Figure 6.14. The brines found at depths greater than 250 m below the surface can reach concentrations as high as 300 g/L and densities of 1.2 kg/L. The variation in brine viscosity can be more than one order of magnitude.

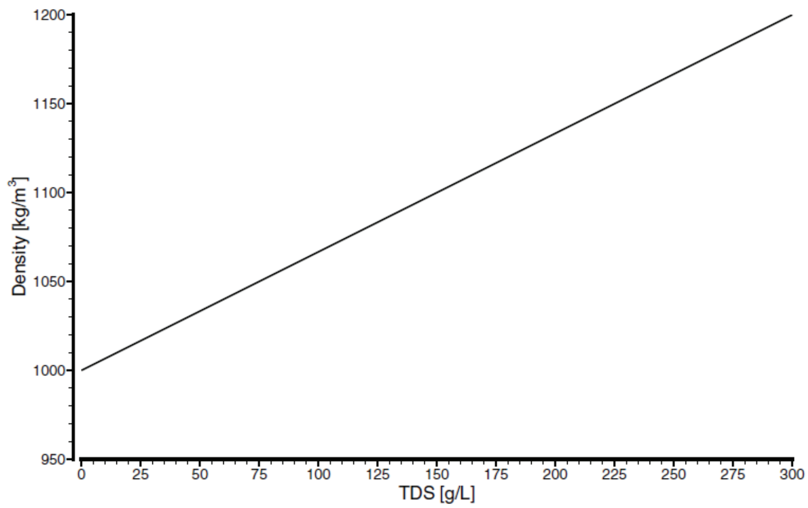

Figure 6.14: Conceptualized relationship between density and concentration.

Normani et al (2007) demonstrated that the presence of dense brines at depth can act as an impediment to flow. The ability of increased brine density to impede flow is illustrated in Figure 6.15, which shows cumulative frequency plots of mean lifetime expectancy (MLE) at increasing depths, with and without coupled density. MLE is an estimate of the time required for a water particle at a given position in a domain to reach an outflow point, and it is a parameter that can be used as a performance measure to assess the state of a groundwater system.

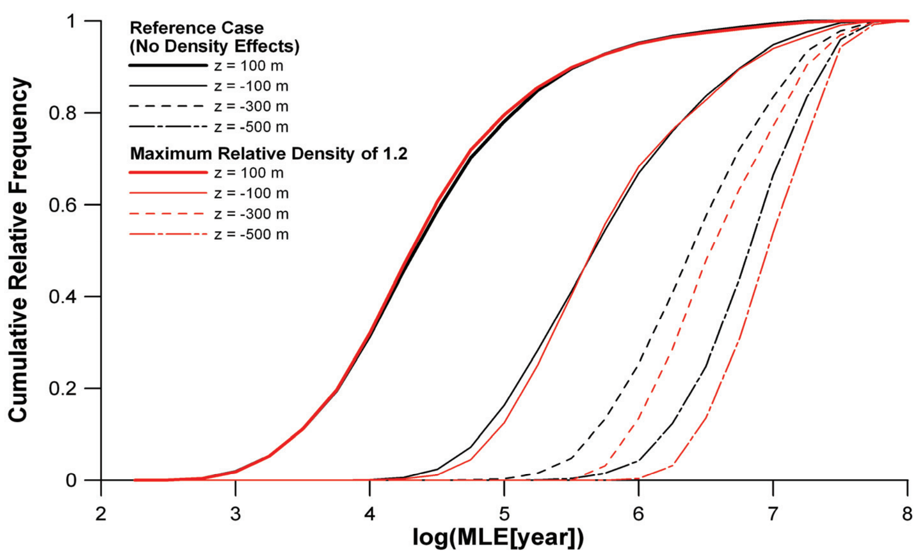

Figure 6.15: Cumulative frequency plots for mean lifetime expectancy at four different elevations in the sub-region with and without brine effects (Normani et al., 2007).

At shallow depths, where the groundwater has lower salinity concentrations than those found at depth, MLE is relatively insensitive to density effects. However, at depths, where appreciable salinity concentrations occur, the effect of brine density on MLE is significant.

Sub-regional shield groundwater flow studies (Sykes et al., 2003, 2004, and Normani et al., 2007) have provided insight into the influence of geosphere properties on groundwater system evolution. The impact of fracture zone properties was investigated by performing uncertainty analyses on fracture zone permeability, width and porosity, with MLE being used as the performance measure. Fracture network models created by Srivastava (2002b) were imported into the numerical groundwater model to capture the regional fracture distribution. Of the three fracture zone properties, permeability had the most significant impact. It was established that using uniform fracture zone permeabilities with characteristics typical of near-surface conditions can potentially underestimate the MLE (Normani, 2009).

During a glaciation event, an ice layer of more than 4 km may be present on a land mass, resulting in a large mechanical load being applied to the geosphere. This load will be transmitted to the elastic porous media and pressurized pore fluids within the interconnected voids. Solving for the compression of the rock and the increase in pore pressure using hydromechanical (HM) coupled equations provides a robust representation of the geosphere processes and realistic models and results. Using the one-dimensional loading approximation in FRAC3DVS-OPG, Normani et al. (2009) investigated the impact of HM coupling in paleo-climate simulations. Figures 6.16 and 6.17 show a block cut of pore velocity magnitudes under glacial conditions respectively with and without a loading efficiency term. When mechanical coupling is not included into the numerical model, the increased velocities due to the glacial boundary conditions result in greater depth of penetration of recharge.

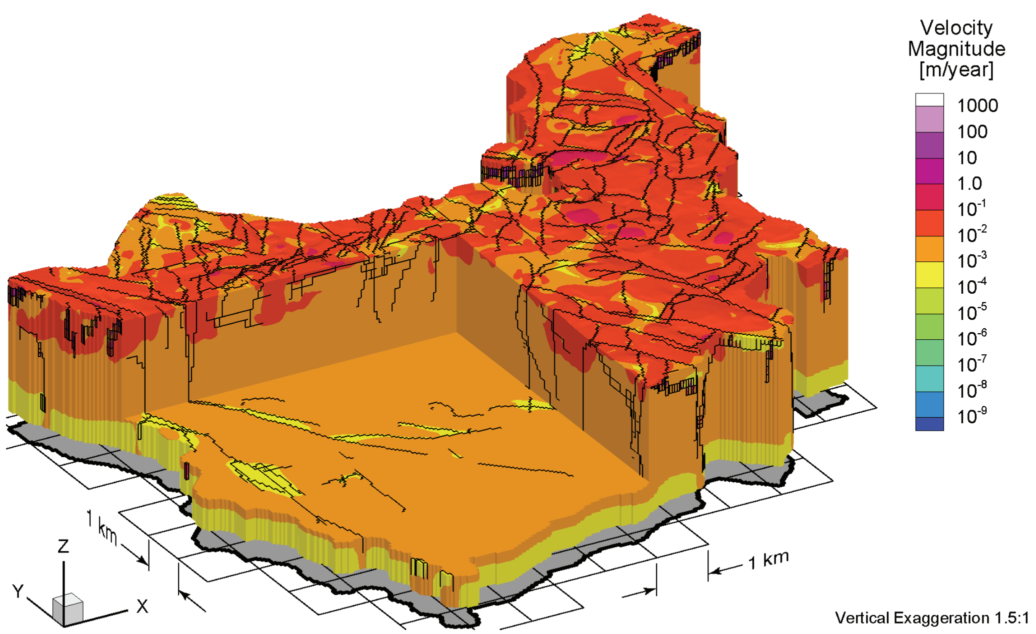

Figure 6.16: Block cut view of pore velocity magnitudes during glacial conditions with a loading efficiency term.

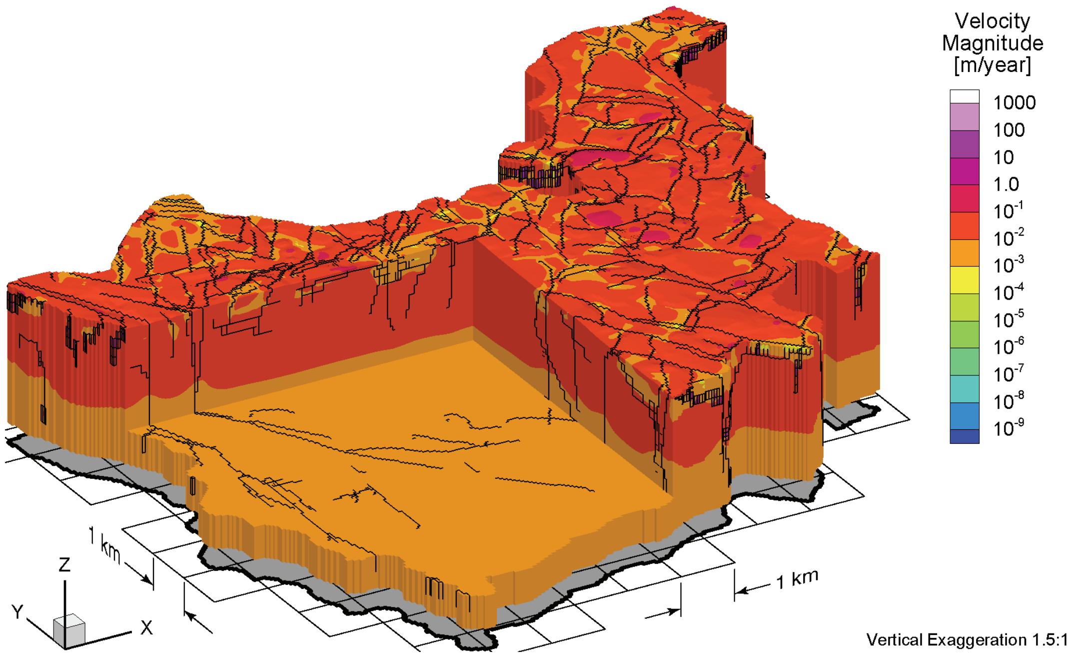

Figure 6.17: Block cut view of pore velocity magnitudes during glacial conditions without a loading efficiency term.

THM modelling was undertaken for Task E of the Decovalex Project. The Decovalex project is a systematic numerical case study of the subsurface THM processes and mechanisms arising from long-term climate change that focuses on predicting magnitudes and rates of change in groundwater flow and state of stress due to glaciation. Studies conducted by Chan and Stanchell (2008) found that the increase of hydraulic head under ice loading, primarily caused by consolidation effects, is not equal to the total stress imposed by the glacier on the bedrock, but rather is about 1/3 of the glacial basal normal stress, in part due to the ratio between the compressibilities of the rock and the water. Decovalex Task E also investigated anomalous pressures found at depths in crystalline rock environments. The results indicated that a temperate glacier, very low permeability rock and limited fracture zone connectivity were necessary for anomalous heads to persist at depth for long periods of time after glaciation.

Rationale for Future Work

The future work program on groundwater flow system evolution within fractured crystalline and sedimentary settings will enable NWMO to maintain and expand Canadian expertise in deep groundwater system modelling, improve groundwater modelling tools and develop methodologies to undertake hydrogeologic site characterization. Tools and methods to quantify groundwater velocities within a host rock formation need to be further developed to support the evaluation of potential repository sites. The NWMO work program needs also to develop methodologies to simulate the hydrogeologic evolution at repository depths under future climate scenarios such as glaciation, in order to assess their potential impact on the long-term safety of the repository.

Work Program **A**

The following tasks will be undertaken to investigate the evolution of groundwater systems within fractured crystalline and sedimentary settings:

- develop and implement efficient algorithms for thermal-mechanical and flow coupling of systems with discrete fracture zones, and demonstrate their application in paleo-climate analyses;
- Further investigate the impact of variable fluid density on matrix and fracture zone flow as well as model algorithms used to simulate density-dependent flow;
- Investigate the impact of boundary condition conceptualization on groundwater and solute migration where the spatial domain is a sub-set of a larger regional flow system;
- Develop and demonstrate robust methods for analyzing flow at different scales in an integrated framework using sub-gridding and sub-timing;
- Develop and compare alternate performance measures suitable for the analysis and interpretation of flow systems. This will include for example average water particle paths, MLA and groundwater age, tracer releases and transport simulations.
- Investigate the impact of paleoclimate glaciation on groundwater systems that include a gas phase.

Future studies on the role of hydromechanical effects on groundwater system evolution may involve full 3-dimensional coupling, which would be able to take into account variable loading across the geosphere.

6.3 NUMERICAL TOOLS AND METHODS

6.3.1 FRAC3DVS-OPG

State of Knowledge

FRAC3DVS-OPG (Therrien et al., 2010) is an efficient and robust numerical algorithm for the solution of three dimensional variably-saturated groundwater flow and solute transport in discretely-fractured media. The model includes a dual porosity formulation, while discrete fractures are modelled as two-dimensional parallel plates or as fracture zones defined by hydraulic conductivity and width. The numerical solution to the governing equations is based on implementations of both the finite-volume method and the Galerkin finite-element method. The FRAC3DVS-OPG version of the model couples fluid flow with salinity transport through fluid density, which varies linearly with the total dissolved solids concentration.

Important attributes of FRAC3DVS-OPG include: the ability to describe arbitrary combinations of porous, discretely fractured and dual porosity media; flexible pre- and post-processing capabilities; accurate handling of fluid and mass exchanges between fractures zones and matrix, including matrix diffusion effects and solute advection in the matrix; fluid and solute mass balance tracking; and adaptive time-stepping schemes.

Other attributes added in previous work supported by the NWMO and OPG include: sub-gridding and sub-timing capabilities (Park et al., 2007), and the addition of algorithms to estimate performance measures of groundwater age and life expectancy for the domain groundwater (Cornaton and Perrochet, 2006a, 2006b; Park et al., 2007).

Rationale for Future Work

Numerical groundwater modelling is a valuable tool for characterizing the evolution of a flow system at a potential repository horizon. In order to increase confidence in model results, codes used by NWMO must be maintained, modified, tested and documented in a formal manner.

Work Program **A**

With this objective in mind, a work program was created with the University of Waterloo to ensure that a version of FRAC3DVS, entitled FRAC3DVS-OPG (Therrien et al. 2004) meets the quality assurance requirements detailed in NWMO's technical computing software procedure. The QA work program ensures that any code modification and development occurs in a traceable, documented fashion and that each new version of the code is accompanied by an appropriate version tracking record. FRAC3DVS-OPG Version 1.3.0 was released in 2010.

6.3.2 Hydromechanical Enhancement of FRAC3DVS-OPG

State of Knowledge

A host rock for a potential deep geologic repository will be subjected to many stresses over the course of the repository lifetime. These stresses include the in-situ stress of the rock, stresses induced during the excavation of the repository, thermomechanical stress and stress specifically associated with glaciation. In the event of glacial loading, upwards of 3 km of ice may be present on the landmass. The stress from a glacial load will be transmitted to the geosphere and will impact the hydraulic properties of the rock matrix and matrix fluid pressures. These changes will affect groundwater flow patterns and possibly the transport of radionuclides.

Rationale for Future Work

In the numerical code currently used by NWMO (FRAC3DVS-OPG version 1.3.0), the implementation of hydromechanical coupling is limited to the case of purely vertical strain with lateral constraints (Guvanasen, 2007). The assumption of purely vertical loading could yield conservative results in the assessment of hydraulic heads and pore pressures. In order to assess the degrees of conservatism, a fully-coupled THM module is being added to FRAC3DVS-OPG.

Work Program **A**

The first phase of development of a fully coupled THM module for FRAC3DVS-OPG was limited to coupling the processes for the rock matrix. The new module was developed based on the THM formulation of Guvanasen and Chan (2000), and the equivalent poroelastic medium formulation of Guvanasen and Chan (2003). The module was based on the Galerkin finite-element method used in conjunction with the weighted-residuals technique.

The next phase of development will extend the 3-Dimensional THM coupling to discrete fractures. Additional future work will include benchmarking the THM coupled module in FRAC3DVS-OPG against other known THM codes and datasets.

6.3.3 COMSOL Multiphysics Code for Coupled THM Modelling

Stage of Knowledge

The rock mass is a fractured medium and therefore considered as a discrete system. However, there are no closed-form solutions for such geometries and numerical methods must be used for solving practical problems. Different numerical methods have been developed for continuous and discontinuous systems. The continuum systems reflect usually the deformation of the material and the discontinuum systems the movement of the material. The interest is in numerical tools for simulating near-field coupled processes at various scales, taking into account the possible anisotropy of material properties and structures.

Rationale for Future Work

COMSOL (2008) is a finite-element code designed for simulating coupled physical processes. It contains partial differential equation solvers for handling coupled equations and incorporates user interfaces that control meshing and the equation solvers. Simulations are performed within the COMSOL Multiphysics® simulation environment that facilitates all steps, including defining geometry, specifying physics, meshing, solving and post-processing of results.

The current work program has investigated the computational capabilities and accuracy of COMSOL for modelling THM processes in fluid-saturated porous media. The accuracy of the code was established through comparisons with known, exact analytical solutions available in the literature for porous media. The accuracy of the computational routines for multi-dimensional THM problems was also verified through comparisons with solutions for the analogous problems obtained using the finite-element code ABAQUS. It has been concluded that COMSOL compares well to other finite-element codes when solving THM problems for linear poroelastic materials saturated with fluid, and that it has potential as a primary tool for modelling long-term rock behaviour in the repository near-field. Further development work is required to optimize its capabilities for the assessment of regional-scale geosphere behaviour in both crystalline and sedimentary rock.

Work Program **A**

On the basis of the results described above, an evaluation the capability of COMSOL to include multiple fracture zones and the effect of ice sheet loading was initiated in 2010. Also, the code capability to simulate glacial loading-induced fluid flow patterns including the surface deformations due to the glacial loading will be examined. Given the computational tractability issues that can arise when solving complex coupled THM systems, it was found that evaluating multiple THM codes would be of benefit to NWMO.

6.3.4 Simulating Flow and Transport in a Fractured Rock Environment

Stage of Knowledge

The NWMO has been funding research and development to improve approaches and methods to simulate flow and transport at various scales in fractured crystalline rock environments. In the early 2000's, the Moderately Fractured Rock (MFR) modelling task force brought together specialists from AECL, the University of Waterloo and Université Laval to apply their numerical methods for simulating a series of pumping tests and crosshole tracer tests with a large block (approximately 50 m on each side) of moderately fractured rock located at the 240-m level of

AECL's Underground Research Laboratory (Vandergraaf et al., 2001). Collaboration between modelling groups was facilitated through the application of 3D immersive visualization technology (Cotesta and Kaiser, 2004).

Rationale for Future Work

Participation in this task force has resulted in the benchmarking of numerical tools used in the Canadian program against those used several other international programs investigating crystalline rock. Substantial work has been done in the area of conceptual geosphere model development and numerical flow model calibration using detailed field characterization data. Further development of numerical tools is required with a particular focus on methods suitable for describing the inherent uncertainty in the geosphere characteristics determined during site characterization.

Work Program **B**

In a continuation of this effort, NWMO joined the international Äspö Modelling Task Force Task 7 in 2005, funding the Université Laval as a participating modelling group. Task 7 has involved the numerical modelling of hydraulic responses at various scales in the fractured crystalline rock environment located on Olkiluoto Island in Finland. Investigations of Posiva's Onkalo underground rock characterisation facility have generated a large data set which supports the modelling study. The Task 7 modelling activities were subdivided into tasks that addressed progressively decreasing scales. Task 7A was focused on simulating a long-term pump test conducted in borehole KR24, which intersected a domain of several large, interconnected, fracture zones. Task 7B considered a smaller volume of an approximately 400 x 400 m^2 region surrounding a group of boreholes KR14-18 with a borehole separation on the order of 10 m.

The modelling tasks in this project involve simulating hydraulic responses in a series of interference tests completed at a block scale, and in so doing, quantifying the reduction of uncertainty in the properties of the fracture network and further assessing the contribution of Posiva Flow-logging (PFL) to the characterization of the rock mass between the large fracture zones. Task 7C considers small sub-volumes and individual fractures intersecting ventilation shafts of Onkalo. The main goal is to use PFL data to characterize low transmissivity fractures.For Task 7, the Université Laval has used the numerical simulator HydroGeoSphere (Therrien et al., 2009), which is an extension of FRAC3DVS-OPG that can be more readily modified to support research activities.

7 BIOSPHERE

The overall goal of the biosphere program is to describe the most important processes in the biosphere from a radiological point of view in order to assess and minimize the environmental consequences of a repository.

The biosphere is complex and evolves over the time scales of interest. Without a specific site, there is a wide range of possible ecosystems that need to be considered. Due to a historical focus on the Canadian Shield for the repository, the Canadian program has focussed on ecosystems typical of Canadian Shield. These included boreal and deciduous terrestrial and freshwater ecosystems, but not marine, arctic or mountain ecosystems. Currently the program is expanding to consider sedimentary rock.

7.1 CONCEPTUAL MODEL

State of Knowledge

Although the biosphere is complex, ecosystems have certain commonalities. Identifying these commonalities allows the development of representative models or reference biospheres which are sufficiently general to support safety assessments. This, in turn, allows the NWMO to establish whether there will be significant impacts from a repository.

The biosphere is typically modelled as a series of compartments representing different potential "pools" for contaminants. Contaminant transfer between some pools is explicitly modelled (e.g. lake to downstream), while others are modelled by ratios that assume the compartments are in quasi-equilibrium over the time scales of interest. The models provide a simple representation of the biosphere that emphasizes the pathways affecting man and human food. The impacts are calculated for a critical group living near the repository. Comparisons with non-human biota can also be used as additional indicators. Although such compartment models offer a simplistic representation of the biosphere and the validity of the transfer factors is limited to the conditions under which the empirical data was collected, they provide useful and simple indicators of potential impacts.

The transfer between compartments is usually based on mass balance equations, including the flow of materials such as oxygen, carbon dioxide, water and nutrients, and the proportional flows of radioactive isotopes that can be associated with these material flows. In general, good estimates can be made of the element concentrations in different compartments and organisms. Many of the important input variables are measurable in the field, for example the geometry of the catchment areas, insolation, water balance, and the composition of ecosystem components.

More sophisticated versions of these biosphere models are coded into Canadian guidelines, notably CSA N288.1 (CSA, 2008).

The alternative approach is the use of process-based models, which allows a more detailed analysis that is relatively independent of specific observations. Some countries have developed process-based, detailed models to support their safety assessment, notably SKB in Sweden. There is also international interest in evaluating the effects of evolving biospheres; for example, representation of the effects of coastal uplift in Sweden and Finland, or the effects of glaciation. This requires a more detailed representation of the landscape around the site and of the variation in model parameters with time. Recent changes to the Canadian system model have allowed biosphere states to be modelled in support of glaciation scenario analyses.

Rationale for Future Work

The current "transfer factor" biosphere model approach used in the safety assessment is generally consistent with international practice and with Canadian guidelines such as the CSA N288.1 standard for nuclear station impact assessment. However, this is a simplified representation of biosphere processes and it is necessary to make sure that the model remains current with international practice. Therefore, improvement of the current model should be part of the NWMO work program.

Work Program **A**

In the near term, NWMO will continue using the reference transfer-factor-based model, presently coupled into the safety assessment CC4 system model. Current focus is on the most exposed group living near biosphere discharge points from the repository. This is sufficient to provide a conservative estimate of potential repository impacts, and the short-term plan is to continue to improve the current model. In particular, the work will address conservatisms due to historical simplification of the biosphere, and will extend the model to represent further landscape features.

An AMBER biosphere stand-alone model is also available that contains the full CSA N288.1 model, and will continue to be used as a working tool to develop and test alternative, more detailed representations of the biosphere.

The work program will also monitor developments in process-based biosphere and in landscape biosphere models. This will include participation in international working groups, such as BIOPROTA.

7.2 TERRESTRIAL ECOSYSTEMS

State of Knowledge

Terrestrial ecosystems include farmed fields, forage fields or pasture land, forests and wetlands.

Releases from a deep geologic repository are likely to impact the environment through initially a groundwater pathway. The pathway into the environment is then through groundwater and water table, through irrigation, or through releases to and deposition from the atmosphere.

If irrigation is possible then this is likely the most important pathway – at least for gardens and forage fields. Otherwise contaminants must reach surface at shallow water table or other discharge locations.

The current NWMO biosphere model has simplified representations of upland soils and wetlands with irrigation from either groundwater or a nearby surface water body. These are modelled as time-independent entities with equilibrium transfer factors between the contaminated input water and any crop or forage products.

Based on the three major Canadian safety assessment case studies conducted to date, the radionuclides most likely to reach the biosphere are relatively mobile, long-lived species, such as radioisotopes of iodine, chlorine, neptunium, uranium and its radium/radon daughters, as well as elements like selenium or technetium in certain cases. From 2002 to 2006, a series of literature reviews were conducted by NWMO in which the reference values for important biosphere transfer rates for the above elements were assessed and updated. One of the findings from these reviews was that there were relatively few data for some important transfer factors, in particular, for Iodine-129. As a consequence of the above findings, a three year sampling program was initiated in 2007 using a newly developed technique to quantify iodine. The sampling included farm animals and plants, and fish and game animals. Data on about 50 other elements were also obtained. In a number of cases, this work represents a significant increase in the amount of data on I-129 and other elements. As an example, the improvement in the data on I-129 in fish is illustrated in Figure 7.1.

The iodine transfer data program has been in place since 2006. The program has been successful in improving the quality of available iodine data. In addition, the data includes biota of direct relevance to Canadian conditions. This work concluded at the end of 2009 with a comprehensive report summarizing the results of the study (Sheppard et al. 2009).

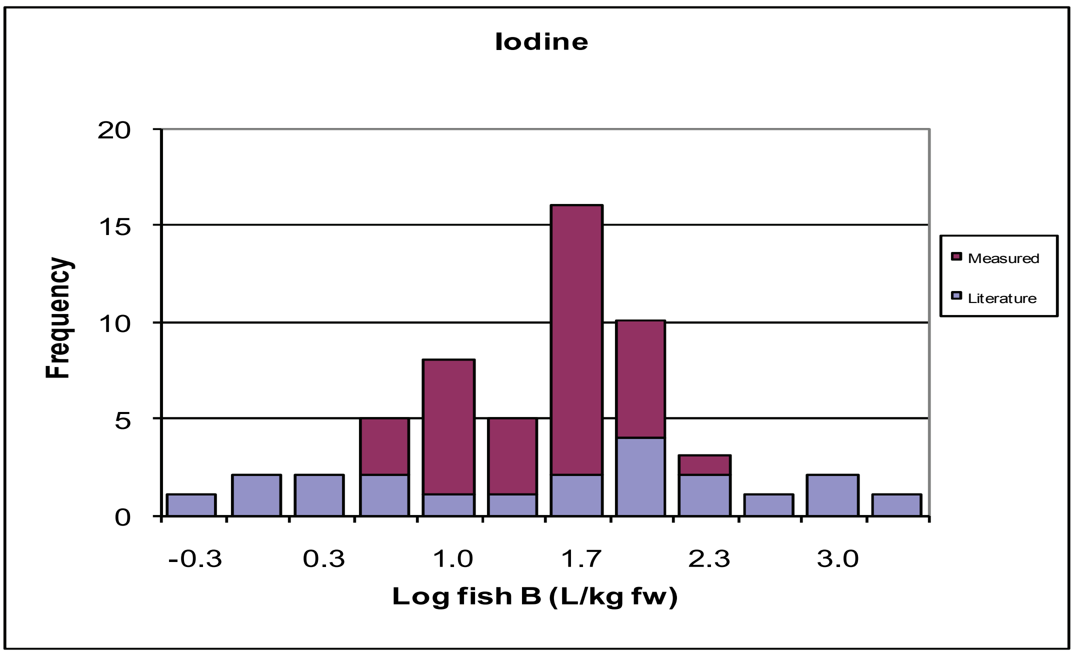

Figure 7.1: Iodine transfer factor data from the literature (blue) compared to additional transfer factors measured by Sheppard et al. (2009) from 2007-2009.

Rationale for Future Work

Recently, the IAEA also released an update to its reference biosphere parameter data, and a new release of the CSA N288.1 standard was issued with recommended generic parameters. Based on the recent work by NWMO and these recent IAEA and CSA reviews, it is likely that the main biosphere transfer factor data needs have been addressed, at least for generic sites in southern and inland Canada. The results need to be reviewed, integrated with international data, and integrated into the Canadian safety assessment reference dataset.

It is possible that consideration of the range of possible sites and of future climate states will lead to a need to assess and improve data for other ecosystems with, for example, a closer focus on permafrost/tundra conditions.

The next significant step in the program, following this detailed parameter view, is to look at the overall processes for key nuclides to ensure that all the key processes are understood and appropriately represented within the models, consistent with international practice.

Work Program **B**

Additional data would be acquired on an opportunity basis, when it can be efficiently coupled to an international project. The main NWMO on-going task in this area is to review the recent compilations of data, and integrate them with international data, in part through publication and presentation at international meetings. The resulting peer-reviewed data will then be added to the Canadian safety assessment reference datasets.

With respect to overall biosphere processes, opportunities to test or validate the current models will be explored, both via the use of field data and through code comparisons. This can be accomplished through working groups such as BioProta, looking at particular radionuclides.

7.3 AQUATIC ECOSYSTEMS

State of Knowledge

Aquatic freshwater systems (running waters, lakes) are generally adequately understood with respect to contaminant transport. However, modelling of the sediments is important. In many discharge areas since the radionuclides will pass through a sediment layer before reaching the waters. In other cases, the radionuclides may settle into sediment layers. In this way, the sediments may exercise a strong influence on radionuclide transport. In the short term, these processes will tend to reduce the outflow of radionuclides and result in lower doses. In the long term, however, radionuclides can accumulate in sediments, only to be released later due to land uplift, resuspension or the draining of lakes and use of sediments as agricultural soils.

Recent work on biosphere transfer factors described in Section 7.2 also included parameters relevant to aquatic freshwater systems, in particular fish and aquatic plant transfer factors.

Rationale for Future Work

The rationale described in Section 7.2 applies for aquatic ecosystems in general. However, important to aquatic systems are processes related to sediments. Also, if candidate sites are considered near coastal areas, then work on marine ecosystems would be needed.

Work Program **B**

The work program parallels that described for Terrestrial Ecosystems in Section 7.2. In the near-term, it will be primarily an integration of recent data and an update to our reference biosphere dataset. It may include participation in international projects that provide opportunity to further validate our understanding of relevant processes.

7.4 NON-HUMAN BIOTA

State of Knowledge

Historically, the Canadian program has focused on assessing the effects on humans. It was expected that humans were a good indicator for potential harm to the biosphere – that keeping impacts low for humans would also protect the environment. However, while this may be generally true, the current approach is to explicitly evaluate impacts on the environment in general, and on non-human biota in particular. This requires more information on biota, as well as appropriate criteria.

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

The screening would be carried out by comparing estimated radionuclide concentrations to these NECs, which are threshold criteria. Because of the conservative nature of the assumptions used to derive the NECs, there is confidence that despite uncertainty in environmental concentrations there will be no significant ecological effect on biota as long as the NECs are not exceeded. In the event NECs are exceeded, a site-specific Ecological Risk Assessment would be required to determine whether this is due to conservatism in the assumptions, lack of sufficient data or a potential real impact.

The screening methodology assessed three representative ecosystems of which the boreal ecosystem is illustrated in Figure 7.2. The modelling and the recommended NECs are described in Garisto et al. (2008).

Work Program **B**

The NEC approach is being updated with new data, extended to include other species, plus extended to include other radionuclides. The whole area of modelling of non-human biota is of current international interest, and developments in Canada, EU and ICRP in particular will be monitored.

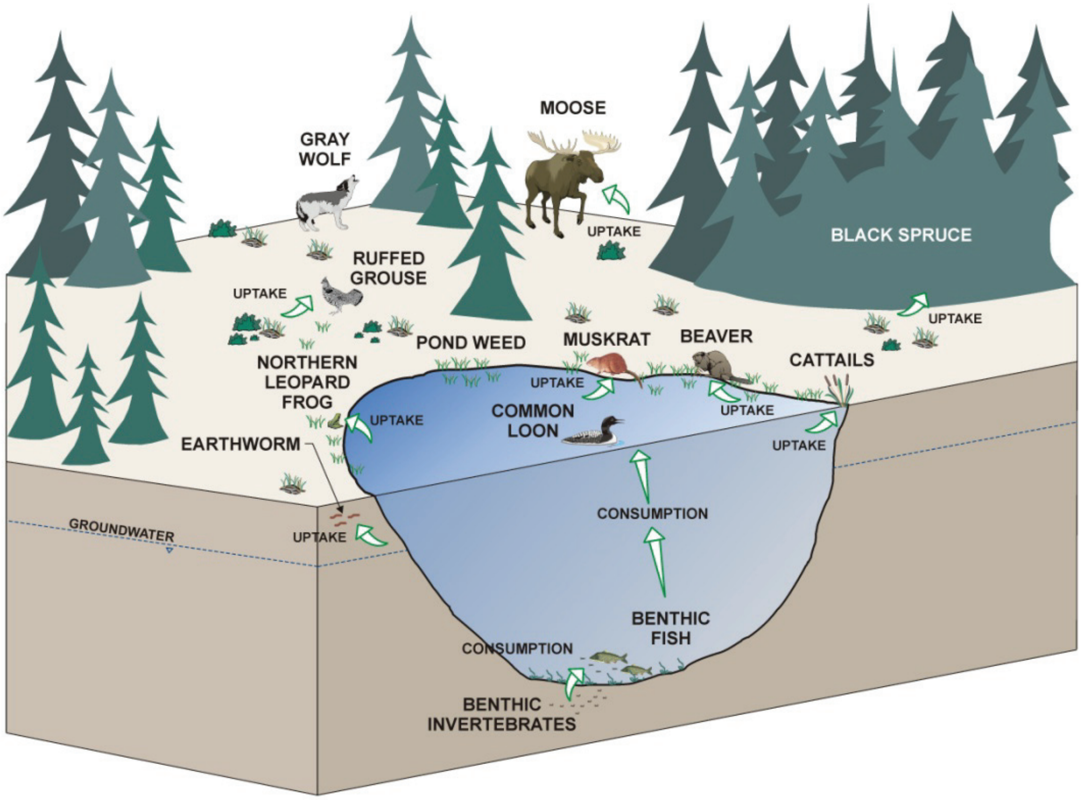

Figure 7.2: Illustration of boreal forest ecosystem conceptual model (Garisto et al. 2008).

7.5 LONG-TERM BIOSPHERE EVOLUTION

State of Knowledge

Biospheres evolve on relatively short time scales with respect to repository safety assessment time scales. Ecosystems could change from boreal to deciduous or scrub in timescales of several hundred years, particularly in response to regional climate changes such as warming or cooling trends. Particularly significant factors that could be relevant in the near-term include the influence of land uplift/sea level changes and of climate change.

Previous Canadian studies have emphasized inland areas, so the influence of sea level changes has not been important. In contrast, in other countries like Sweden and Finland, the shoreline displacement with time is a critical factor in the biosphere model. If sites are considered that are near the ocean, then the implications of sea level changes will need to be incorporated into the biosphere models.

In the near-term, the main climate change of interest is global warming. This could affect the pattern of rainfall and seasonal temperatures, and therefore the surface water flows and specific ecosystems. However, broadly speaking, southern/central/eastern Canada is likely to remain in a similar temperate climate state and the postclosure safety assessment biosphere models currently used are likely to continue to be relevant.

For Canada and for timescales of interest to repository safety, the most significant credible long-term variation is climate change leading to glaciation. Within the past one million years, much of Canada has been ice covered in a series of nine major ice ages. Each glacial cycle likely included several ice sheet advances and retreats through a given region. Current understanding of glacial cycles in Canada is discussed further detail in Chapter 8.

An ice age obviously causes large variations in the biosphere. The current temperate climate over much of southern/central/eastern Canada reflects interglacial conditions. However over the past one million years, much of the time the Canadian land surface was covered either with permafrost or an ice sheet. Thus the biosphere processes that are relevant now under temperate climate conditions may not be representative of conditions over most of the next one million years.

However, temperate climate based biosphere models are still very appropriate for repository safety assessment since, first, there is interest in the potential impacts in the near future (tens of thousands of years) where the climate is most likely to be temperate in southern/central/eastern Canada. And secondly, temperate climates are consistent with an agricultural lifestyle in which the impacts of a repository might be maximized through locally grown crops and domestic animals. In contrast, the cool climate conditions associated with permafrost are likely to have reduced crop yields and therefore lead to lifestyles which use resources from extended areas, which in turn result in lower impacts from any repository. That is, the self-sufficient temperate-climate farmer is a useful and generally conservative indicator of potential repository impacts. Recent safety assessments have therefore used a steady temperate climate assumption so that the long-term impacts of a repository could be reasonably gauged using a currently relevant and sensitive indicator.

Recent New Knowledge

NWMO has recently completed a glaciation scenario modelling exercise designed to improve quantitative assessment of the potential impacts of glaciations. In this case, a hypothetical repository was assumed on the Canadian Shield, and the effects of glaciations were modelled over a 1 million year period, including multiple ice ages. Contaminant transport within the geosphere was modelled in detail using FRAC3DVS, and then the CC4 system model was used to calculate doses. The impact on humans was assessed by using a series of stylized biosphere states appropriate for each portion of the glacial cycle: temperate, permafrost, ice sheet and proglacial lake.

The results show that a self-sufficient temperate-climate farmer using a well for water supply is a reasonable indicator of potential impacts, compared to other exposure groups that are relevant to the conditions occurring during much of a glacial cycle. It may therefore not be necessary at the early site assessment stages to include detailed glacial cycle biosphere and dose models.

Work Program **B**

Although no major concerns over dose impacts during permafrost periods have been identified, the recent modelling was based on limited tundra biosphere data. Opportunities to obtain further data on the main food chain pathways for humans under tundra conditions are of interest, especially the air-lichen-caribou pathway.

7.6 ASSESSMENT CRITERIA

State of Knowledge

With respect to radiation and human health, NWMO follows the recommendations of the CNSC and international bodies such as ICRP. These recommendations provide a well developed structure for dose impact assessment that reflects the current international consensus on radiobiology and the effects of radiation.

There is also international consensus on the value of complementary indicators of impact other than dose for long time frames. In particular, radionuclide concentrations in surface waters or fluxes from geosphere are often reported in repository safety assessments. This approach requires background radioactivity information to identify appropriate reference values.

The primary risk from a repository is from the radioactivity. However the waste does contain chemical elements that are potentially hazardous, notably uranium. The methods to test for possible chemical toxicity impacts are not as well developed as those related to radiation effects.

Rationale for Future Work

In this area, NWMO needs to stay current with recommendations by international and Canadian regulatory authorities and with enhancements to international databases. The main tasks required in the near term are identified below.

Work Program

A

To meet the stated program needs NWMO will carry out the following tasks:

- Update the dose conversion factors in the reference dataset with the latest ICRP recommendations as they become available.

- Continue current work to map out the key natural radioactivity levels in surface media across Canada relevant to long-term indicators of safety.

- Maintain awareness of developments in criteria for evaluating chemical toxicity.

8 SAFETY ASSESSMENT

Safety assessment evaluates the operational and long-term safety of the facilities for long-term management of used nuclear fuel, and in particular for a deep geological repository. In the near-term, before a site has been proposed and a repository design has been selected, the safety program evaluates case studies. These provide a basis for development and testing of analytical tools, and for understanding the likely important features and processes which in turn aids both siting and design selection.

Safety assessment includes analyses of both normal operation and accidents during facility operation and of both normal and disruptive scenarios after repository closure. It includes the assessment of potential impacts on workers, the public and non-human biota, from both radioactive and chemical hazards.

The overall performance of the repository is analysed through a system-level model. The sections that follow describe the system model, as well as recent and future work involving case studies.

8.1 SAFETY FEATURES

A set of key attributes of a deep geological repository relevant to long-term safety is listed in Table 8.1. Consistent with the nature of the hazard and containment behaviour, safety assessments are typically carried out for time scales of about one million years. Therefore, features, events and processes that could affect the attributes listed in Table 8.1 are evaluated on such a time scale.

Table 8.1: Typical Physical Attributes Relevant to Long-Term Safety

- Repository depth providing isolation from human activities
- Site low in natural resources to eliminate reasons for intrusion
- Durable waste form (ceramic uranium oxide pellets)
- Robust container
- Self-sealing clay seals
- Low-permeability host rock
- Spatial extent and durability of host rock formation
- Stable chemical and hydrological environment

8.2 POSTCLOSURE SAFETY

8.2.1 System Model

The postclosure safety assessement is supported by several computer codes and datasets. The main codes used by NWMO for postclosure analyses are listed in Table 8.2.

Table 8.2: Main Safety Assessment Codes for Postclosure Analyses

Software	Description
SYVAC3-CC4	NWMO reference postclosure system model
FRAC3DVS	3D groundwater flow and transport model
TOUGH2	3D two-phase gas and water flow model
AMBER	Generic compartment model
COMSOL	3D multi-physics finite element model

The main Canadian postclosure system model, SYVAC3-CC4, is used for assessment of scenarios in which groundwater transport is the key pathway for release of radionuclides from the repository to the surface. This system model includes all key processes, from the used fuel, through container and near-field, through the geosphere, and the biosphere. It provides full support for deterministic and probabilistic assessments.

SYVAC3-CC4 is supported by other codes, notably FRAC3DVS (3-D groundwater flow and transport modelling), TOUGH2 (3-D two-phase water and gas transport), input/output tools (SINGEN, SYVIEW), and a reference dataset containing model parameters and settings.

The code is divided into an executive shell and math library (SYVAC3), and three submodels with each segment interacting with the next. These three submodels are the vault, geosphere and biosphere submodels. These can also be modified to represent additional alternative scenarios (e.g., human intrusion) or used as screening models.

8.2.2 Vault Model

The vault submodel includes models of fuel dissolution, container failure, and transport of radionuclides through an engineered barrier system consisting of buffer, backfill, excavation damage zone (EDZ) and into the immediate (near-field) rock. Since the radionuclides in the fuel decay and the inventory constantly changes, the time-dependent radionuclide inventories are calculated based on the known properties of the numerous nuclides and their subsequent decay chains. Both instant release and congruent dissolution models are considered (see Section 3.2); radiolytic degradation of the waste form, solubility limited releases, precipitation and sorption of radionuclides are all modelled.

The radionuclide releases from the used fuel containers occur after an estimated vault saturation time. Water is assumed to access the fuel by first penetrating the outer container shell through a defect in a small number of storage containers (McMurry et al. 2004). The number of failed containers is based on a probabilistic model which calculates the fraction of containers that could have an undetected defect.

The current vault model treats the buffer, backfill, excavation-damage zone (EDZ) and vault geometry as cylindrically symmetric. The buffer is modelled as a diffusion-dominated segment while the backfill and EDZ allow flow components calculated using Darcy’s law and an equivalent-resistance model (Johnson et al. 1996). The resulting flux of radionuclides out of the EDZ and near-field is passed onto the geosphere model.

8.2.3 Geosphere Model

The geosphere submodel interacts with the vault submodel and represents the geosphere component of the repository; tracking nuclide transport through the rock fractures and groundwater flow paths (Johnson et al. 1996, Garisto et al. 2005a). The groundwater flow pathways are not directly calculated in the CC4 model; they must be determined externally using an appropriate groundwater flow code (for example, FRAC3DVS-OPG, Section 6.3), and the flow results then used to generate the CC4 geosphere model. The CC4 model uses a three-dimensional description of the contaminant transport pathways, which is input as a network of nodes connected by one dimensional transport segments. Each segment of the transport network is assigned constant physical and chemical properties. Transport properties can vary from segment to segment along the transport pathway and if required they can change as a function of time in a stepwise manner.

The benefit of the CC4 model is that simulations run much faster so it allows for probabilistic transport calculations within a given defined groundwater flow system, while FRAC3DVS-OPG provides a more detailed representation of the groundwater system suitable for deterministic analyses. As typically used in case studies, the FRAC3DVS-OPG and CC4 model results are calibrated against each other to ensure that the CC4 simpler representation is appropriate.

In addition to modelling natural groundwater flow paths, a water supply well is available in the flow network in CC4 and can be included or excluded from a given analysis. In addition radionuclide discharges to the biosphere can occur to surface waters, to terrestrial areas near surface waters, to bogs (wetland), and to the atmosphere (gaseous discharges).

8.2.4 Biosphere Model

Once radionuclide fluxes to the biosphere have been calculated, the fluxes are passed to the biosphere submodel to calculate concentrations and doses. The doses to the critical group, i.e., the most exposed group of individuals are calculated. Typically the critical group lifestyle is based on a hypothetical self-sufficient farm family assumed to be living near the repository.

The biosphere is modelled with nuclides collecting into a well and a nearby surface water body (i.e. lake or river). The surface water is modelled as well-mixed, with four contaminant loss routes: a defined outlet discharge rate, sedimentation, radioactive decay, and gaseous evolution from the water surface.

The soil model calculates the concentration of each nuclide in the rooting zone of the soil in the four field types that may be used by the reference human group – the garden, the forage field, the wood lot and the peat bog. The soil concentration considers both contamination from atmospheric deposition and from irrigation, as well as from contaminated groundwater that discharges from the geosphere to the surface. From the soil, the nuclides can be transferred to plants, animals and humans, and a dose is calculated from a food-chain model and from external exposure pathways. Dose pathways assess both internal and external radiation exposures for the reference human group and non-human biota.

Currently, human intrusion is also considered using a simple model represented in AMBER. It assesses the consequences from inadvertent human intrusion into a repository as a result of a borehole intercepting a used fuel container in the repository and bringing used fuel debris to the surface (D'Andrea and Gierszewski 2004). The Radionuclide Screening Model (RSM) is another simple system model that utilizes the SYVAC3 framework to screen out radionuclides that would pose no significant radiologic risk to a member of the public living near the repository. This allows more detailed safety assessments to focus on the radionuclides of significance (D'Andrea 2001).

Recent Work

A significant software development was the addition of "states" to the SYVAC3-CC4 system model so that it could be used to evaluate the effect of time-dependent changes in both geosphere and biosphere conditions, such as those that would take place during a glacial cycle. Each "state" represents a particular realization of future geosphere and biospheres, for example, a "permafrost state" considers the case in which the climate has cooled and permafrost has formed. In such case the geosphere differs from today's conditions in that the permafrost layer is essentially impermeable and so there is no water movement through it. Under such conditions the biosphere is more representative of a northern tundra climate than today's boreal forest climate on the Canadian Shield.

Rationale for Future Work

Although the main SYVAC3-CC4 system model is complete, updates continue to be made to broaden the functionality, improve accuracy and incorporate changes to the reference repository design. NWMO safety assessment codes are maintained under a software quality assurance system consistent with CSA Standard N286.7. NWMO has a formal verification process for changes to SYVAC3-CC4.

Work Program A

Validation of the safety assessment system model is an ongoing task. Opportunities for further validation of specific process models or overall system-level code comparison are performed when possible.

As a long-term alternative to SYVAC3-CC4, the option of switching the repository system model to a commercial software platform such as COMSOL will be investigated. By using a code like COMSOL, geometries could be more accurately represented and groundwater flow self-consistently calculated, along with the other elements of the system model. Also such codes provide the ability to separate the tasks of maintaining the numerical solvers state-of-the art, with maintaining the system-level model. The numerical solvers are in effect maintained by the code developer, and shared among a wide number of users, while NWMO focusses on the repository safety model. The suitability of COMSOL for NWMO-specific applications will be explored in the near-term.

Planned additions to the functionality of the system model include an improved fuel dissolution model consistent with the fuel dissolution research being done at the University of Western Ontario (see Section 3.2). Also, an improved model for container failure and near-field transport is planned. A revised biosphere model is also scheduled to be included in the system model.

8.2.5 Gas Generation and Transport

Most radionuclides are not volatile. The main pathway for radionuclide release is through dissolution and transport in groundwater. The state-of-knowledge and ongoing work programs with respect to groundwater modelling are described in other sections of this report.

Gas may be generated by various processes in the repository near-field, including radioactive decay, radiolysis and corrosion. Of these, only corrosion of metals, notably of steel containers, is potentially significant in terms of total gas generation. Current knowledge of steel corrosion under repository conditions is described in Section 5.1.2.1. The movement of gases generated within the repository will depend on the repository seals and on the surrounding geosphere.

Work Program **A**

NWMO is participating in projects to benchmark numerical models for gas generation and transport under repository conditions. This presently includes participation in the LASGIT experiment at the Aspo underground research laboratory in Sweden, in the HG-A experiment at the Mont Terri underground research facility in Switzerland, and in the European FORGE project numerical benchmark tests.

8.2.6 Thermodynamic Database

Understanding the long-term stability of the system requires knowledge of the thermodynamics, as this defines what reactions are energetically favoured. This information can be used to understand dissolution and precipitation, alterations of the repository seals, and changes in the minerals within the host rock as a result of repository or future climate change influences. This information is also useful to understand processes that have occurred in the past at a given site. The work program associated with developing and maintaining a thermodynamic dataset is described under Section 3.3.2.

8.3 PRECLOSURE SAFETY

Safety during the construction and operational period is also assessed, as part of providing feedback during the design process as well as supporting the licence application. Topics include conventional non-radiological safety, normal operations, worker dose and optimization for ALARA, transportation safety, and malfunctions and accidents and malevolent acts.

In the context of a geological repository and related facilities for used fuel, these topics were last addressed in detail as part of the EIS (AECL, 1994), and reviewed as part of the NWMO study (NWMO, 2005),

Work Program **A**

An updated transportation risk assessment will be carried out to provide a current reference, and to support transportation system and facility planning. The preclosure safety assessment will be updated in parallel with the ongoing work to develop more detailed plans for operations and surface facilities.

8.4 CASE STUDIES

The objective of safety case studies is to provide illustrative examples of repository safety under hypothetical conditions as well as to test and demonstrate the safety assessment approach. Three major safety assessment case studies completed within the Canadian program are:

i. Environmental Impact Assessment (EIS) study (AECL 1994),
ii. Second Case Study (SCS) (Goodwin et al. 1996); and
iii. Third Case Study (TCS) (Gierszewski et al. 2004).

These case studies have provided an opportunity to assess and illustrate the safety implications of the deep geological repository concept in the Canadian Shield. Each of the above studies considered a different combination of engineering design and site characteristics.

8.4.1 Recent Work

The NWMO reference time frame used for the long-term safety assessment of deep repositories is one million years, a period roughly equivalent to that required for the radioactivity in used fuel to decrease to that due to its natural uranium content. Over the past one million years, the most significant natural events across Canada have been repeated glaciation cycles, which have occurred approximately every 100,000 years. It is likely that current greenhouse gas levels will delay the onset of the next glaciation (Archer and Ganopolski 2005; Berger and Loutre 2002), but for the purpose of assessing repository safety it is prudent to assume that the glacial cycles will eventually resume since they are driven by long-term variations in the Earth's orbit.

In previous Canadian case studies, the effects of glaciation have been considered in geoscience studies and in engineering the design of the repository. The potential impacts of glaciation on safety and performance have also been evaluated qualitatively but not quantitatively. Therefore, starting in 2007, the effects of an evolving climate with multiple glaciations have been quantitatively evaluated, from a safety assessment perspective, within the context of the hypothetical Third Case Study site on the Canadian Shield. The purpose of this “Glaciation Scenario” case study was to quantitatively assess the long-term dose implications of glacial cycles for a deep geological repository, and to understand the key factors involved. The results of the glaciation study are published in 2010 (Garisto et al. 2010; Walsh and Avis 2010).

Detailed transient three-dimensional modelling results obtained using the FRAC3DVS code, confirmed the expected impact of glaciation on the velocity and direction of the groundwater flow system (Walsh and Avis 2010). The potential effects of the ice load on transient groundwater flows were included in the calculations through use of the 1-D hydromechanical coupling module in FRAC3DVS (Therrien et al. 2010). The modelled effects were greatest near the surface but extended to the repository level (Figure 8.1). Open taliks during Permafrost States, in particular, are a dominant factor, focussing system impacts at a discrete location. (An open talik is a layer of year-round unfrozen ground that lies in permafrost, generally below a large lake). The transport calculations also indicated that radionuclide mass flows to the surface biosphere are quite different in detail for the transient glaciation model compared to the equivalent constant climate case, although the overall trends are similar.

For the Glaciation Scenario, the safety assessment calculations indicated that the dose rates are highest during the Temperate State (Figures 8.2, and 7.3). This occurs because the critical group during the Temperate State uses a well, rather than a lake, as the source of domestic water, and nuclide concentrations in well water are, typically, significantly higher than in lake water. In the Reference Glaciation Scenario the calculated peak dose rate is approximately 3.7×10^{-7} Sv/a (SYVAC-CC4 model, Figure 7.3), with I-129 contributing the most to the total dose rate. This is similar to the peak dose rate of 1.3×10^{-7} Sv/a for the corresponding constant climate case, and well below the dose rate constraint of 3×10^{-4} Sv/a recommended by International Commission on Radiological Protection (ICRP) for disposal of long-lived solid radioactive waste as well as below the average Canadian natural background dose rate of 1.8×10^{-3} Sv/a (Figure 8.2).

In the Glaciation Scenario, spikes of I-129 are released into the biosphere at the transitions between glacial stages. These spikes are partially caused by pressurization or depressurization of the flow system caused by the advance or retreat of the ice sheet over the site. They are also partially caused by the instantaneous changes in numerical boundary conditions and geosphere properties at transitions between glacial states, which are an artefact of the modelling approach. While the fluxes may change dramatically during transitions, the actual concentrations of these radionuclides does not change as much.

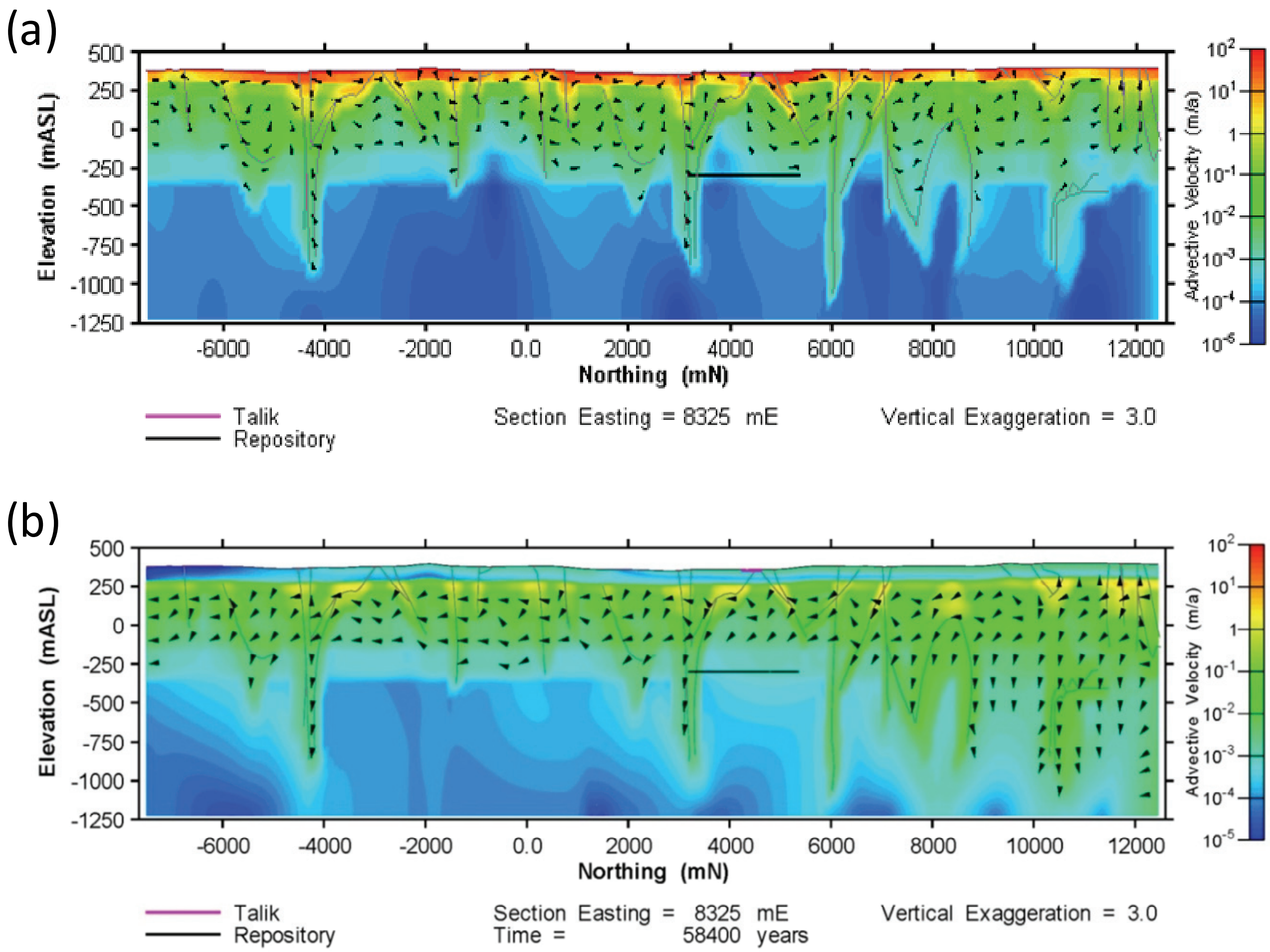

Figure 8.1: Glaciation Scenario Reference Case flow model results during: (a) the initial temperate state; and (b) beginning of ice sheet state. The advective velocity distribution is shown by colour; velocity vectors are plotted where the velocity exceeds 1 mm/a.

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

Rationale for Future Work

The Third Case Study safety assessments for a used fuel repository in crystalline rock assumed that the used fuel containers were placed in the repository using an in-room horizontal placement method. However, the in-floor borehole emplacement method was selected in 2009 as the reference design for a repository in crystalline rock. Thus, a safety assessment of a repository using the in-floor borehole placement method became necessary. The Fourth Case Study, addressing this scenario, is in progress and is expected to be completed in 2011.

Previous Canadian repository designs and case studies considered a used fuel repository located in crystalline rock. NWMO is currently developing repository designs suitable for siting in sedimentary rock. Although broadly similar to a repository in crystalline rock, the sedimentary rock geosphere can change the relative importance of various features and processes. For example, rock stresses, salinity and permeability are likely to be different, each feature having an impact on the repository design and performance. Also gas generation and transport could be different in a very-low-permeability sedimentary rock environment. To understand the safety implications of siting a repository in sedimentary rock, a safety assessment case study for a used fuel repository in sedimentary rocks will be required.

Work Program A

The safety assessment work to be conducted during 2011 to 2013 includes the completion of the Fourth Case Study for crystalline rock and the preparation of a Fifth Case Study assessing the safety of a repository sited in a generic sedimentary rock environment.

In parallel with these specific case studies, NWMO will maintain and improve its approach to preparing safety cases. This includes work to improve the basis for scenario definition such as through Features, Events and Processes catalogs, through understanding of relevant natural analogs, and through involvement in international projects related to safety case methodologies.

9 TRANSPORTATION SYSTEM DEVELOPMENT

The objective of the transportation program is twofold: to develop and evaluate options for the transport of used fuel from interim storage sites to the APM facility with a deep geological repository, and to provide engineering design and logistics to support technical evaluations of candidate repository sites. In the short-term, before candidate sites have been identified, the transportation program objective is addressed through the development of conceptual designs and illustrative case studies.

Much of the existing work has been developed for three modes of transport: road, rail and water (and combinations of these modes) for the movement of used nuclear fuel from the existing storage facilities at reactor sites to a hypothetical repository site. The transportation systems considered were based on existing transport package designs developed and certified by OPG for transport of used fuel by road, rail and water. These packages are briefly described in Section 9.2. New studies will consider the transport of used fuel from existing wet and dry storage facilities and evaluate the potential impacts of the transportation program on workers, the public, the environment and the infrastructure of the communities along potential transport routes.

9.1 TRANSPORTATION SYSTEM STUDIES AND LOGISTICS

State of Knowledge

Previous transportation studies were prepared by Cogema Logistics based on a reference used fuel inventory of 3.6 million bundles and a transportation program of 30-year duration, considering three modes of transport, road, rail and water (Cogema Logistics, 2003a, 2003b). These studies are being updated as required as part of the APM conceptual design and cost estimate update.

The reference transport system and logistics are being updated for the “road-only” mode. Two used nuclear fuel inventory scenarios are being considered: 3.6 million bundles and 7.2 million bundles. The reference case has 3.6 million bundles (NWMO 2005) and the alternate case has 7.2 million bundles (Stahmer, 2009). For both scenarios, fuel transport is assumed to start in 2035, the assumed start of repository operation (for APM conceptual design and financial planning purposes).

Rationale for Future Work

In May 2010, NWMO initiated the siting process for a deep geological repository for Canada’s used nuclear fuel. Further development of used fuel transportation system designs and logistics will be required in support the siting process during the next few years. The used fuel inventories and storage modes at each storage site and future inventory predictions are regularly updated. The bulk of used nuclear fuel transport is planned to be conducted using the existing transport infrastructure in combination with an integrated transportation system. Development of such a system is an integral component of APM implementation.

Work Program

A

Transportation logistics and options for the transport of the used fuel from interim storage sites to a hypothetical APM facility with a deep geological repository will be developed. This work will provide illustrative case studies that will serve to assess the safety, efficiency and cost of used fuel transportation by all viable modes. Upon selection of potential candidate sites, the transportation case studies may serve as a model to develop and optimize detailed transportation system designs and logistics.

9.2 TRANSPORTATION SYSTEM CONCEPTUAL DESIGNS

State of Knowledge

Previous used fuel transport and the system conceptual designs were prepared by Cogema Logistics (Cogema, 2003a). These conceptual designs considered three transportation modes: all road; mostly rail; and mostly water. Transportation system designs based on these modes were developed at a conceptual level. The transportation systems were based on two transport package designs:

- Irradiated Fuel Transportation Cask (IFTC) ; and
- Dry Storage Container Transportation Package (DSCTP).

The IFTC (shown in Figure 9.1) is designed to transport 2 fuel modules. Each module contains 96 fuel bundles. The fully loaded package weight is approximately 35 tonnes and it is suited for transport by road, rail and water. The IFTC was certified for use in Canada and one demonstration package was built in the late 1980s. Its certificate would be upgraded to meet current regulations prior to the manufacture of new units. For its intended future use, a Licence to Transport Category 2 Nuclear Substances would be required.

The DSCTP (shown in Figure 9-2) is designed to transport one Dry Storage Container (DSC), a steel-lined concrete cask used by OPG for dry storage of used CANDU fuel (4 fuel modules) with a total capacity of 384 fuel bundles. The package consists of a DSC, and a reusable impact limiter set. The weight of a fully-loaded DSCTP is 100 tonnes. It is designed for regular transport by rail or water; regular transport by road mode would incur some restrictions due to its size and weight. The DSCTP is certified for use in Canada to the current regulations. In addition to the valid package certificate, a Licence to Transport Category 2 Nuclear Substances would be required for used fuel shipments.

Approximately 5,000 DSCs are expected to be in interim storage at reactor sites in Ontario (base case) at the projected start of the transportation program in 2035, and about 7,000 for the alternate 7.2 million bundle scenario.

Rationale for Future Work

It is necessary for NWMO to ensure that it has up to date transportation system designs, logistics, cost estimates and safety assessments to support the repository siting process. System designs and logistic studies and a Transportation Safety Assessment will be required as transportation routes and associated modes are established.

Work Program

A

The transportation work program will provide a solid framework upon which the transportation system can be built. Transportation systems and logistics will be further developed to support the siting process. Further refinement of system designs and logistics will be required as candidate repository sites are identified and preferred modes of transport are studied and selected.

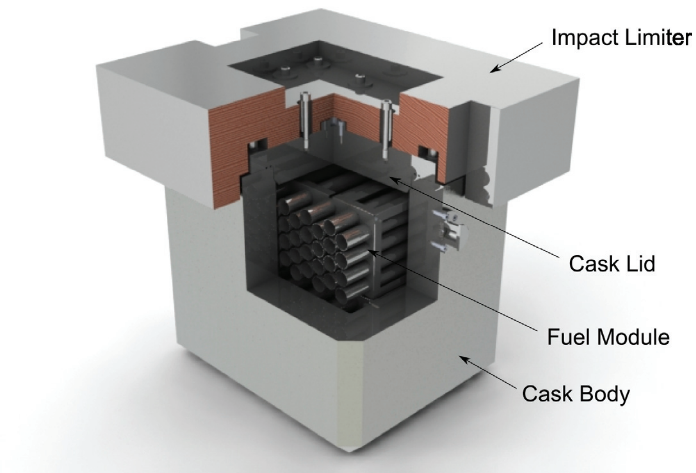

Figure 9.1: Cut-away view of the Irradiated Fuel Transportation Cask.

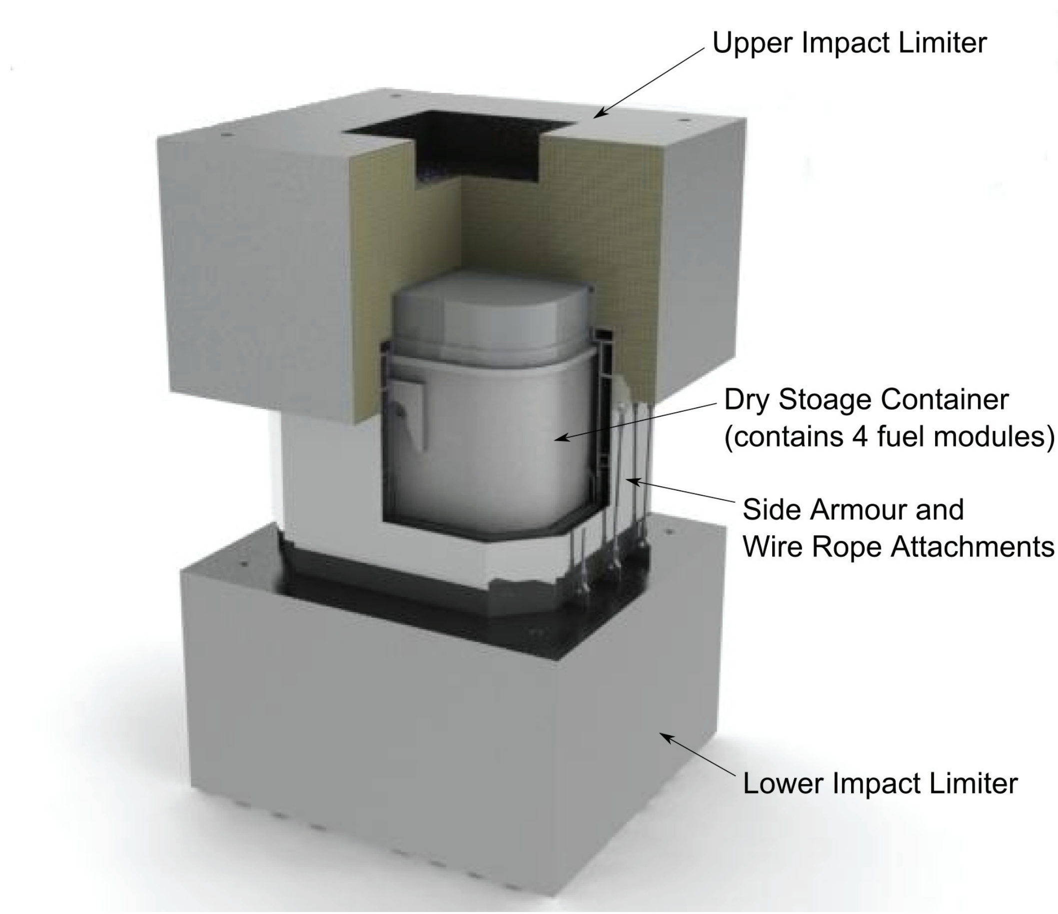

Figure 9.2: Cut-away view of the Dry Storage Container Transportation Package.

10 REPROCESSING, PARTITIONING AND TRANSMUTATION

NWMO continuously monitors developments on used nuclear fuel reprocessing, partitioning and transmutation (RP&T) as alternative technologies that could impact or could be used for long-term management of nuclear fuel waste. This section contains a summary review of the subject based on the most recent reports prepared for NWMO on the subject (Jackson and Dormuth 2008, 2009, 2010).

Reprocessing of used nuclear fuel from today's reactors allows the separation (partitioning) of its components generally into five streams:

a. zirconium-based metal cladding structures, usually set aside for separate disposal;

b. fuel pellets, dissolved in hot nitric acid, with uranium-238 forming most of the mass in the solution, and a much smaller amount of residual uranium-235. The uranium-235 can be recycled in new fuel, but is more commonly stored with the uranium-238;

c. fissile isotopes such as plutonium-239 also present in the solution can potentially be recycled into fresh MOX fuel, but are often left in the solution;

d. both short- and long-lived Fission Products (FP) and neutron activation products are removed as a waste stream and typically incorporated in glass blocks for long-term storage;

e. minor actinides (MA) that have long half lives are candidates for transmutation and the subject of a large fraction of the research work on RP&T.

Transmutation of radioactive isotopes into non-radioactive or stable isotopes is done by bombarding the target isotopes with neutrons or other high-energy particles in a Fast Reactor (FR) or an Accelerator Driven System (ADS). Bombardment with high-energy particles induces fission of the MAs.

Many potential nuclear fuel cycles are possible. Dealing with the MA is one of the most challenging problems in RP&T driven fuel cycles. There are several MA transmutation schemes that can be classified in two main categories: homogeneous and heterogeneous. Homogeneous cycles are those in which the MAs are mixed into the fuel of a fast reactor (FR). Fuel initially containing MAs that has already been irradiated in an FR is further reprocessed and its MAs are incorporated in fresh FR fuel. Several such cycles may be needed to reduce the concentration of MAs in the fuel to the desired levels. Heterogeneous cycles involve the separation of the MAs and their incorporation into targets for irradiation in an FR. These targets typically have very high burnups and multiple cycles are not required. An important advantage of the heterogeneous approach is that it has little impact on the operation of the reactor and does not involve the development of special fuels.

A fuel cycle can be a mixture of both homogeneous and heterogeneous steps. For example, MAs could be present in both the FR fuel and in targets surrounding the reactor. A fuel cycle can have one or two tiers. In a two tier system, the MAs can also be consumed in an Accelerator Driven System (ADS). An ADS consists of an accelerator that produces an intense beam of high energy protons incident on a lead-bismuth target yielding a very large flux of fast neutrons by spallation. The target is in the core of a fast reactor assembly containing plutonium and a relatively large amount of MA. This assembly is only made critical by the spallation neutrons. Ideally the heat generated by the fissioning of the MAs and plutonium could be used to generate electricity. There would be no need to extract the MAs from the plutonium, which is desirable for preventing proliferation. Much larger quantities of MAs could be consumed in an ADS compared to a FR alone.

The spectrum of recycling options is very wide considering multiple recycling of FR fuel. Consequently in the October 2008 NEA P&T meeting in Japan, it was recommended that R&D should focus only on a few reference cases, with internationally agreed roadmaps and milestones. The impact of RP&T on the long-term management of radioactive wastes in deep geological repository continued to be a central theme at this meeting as it had been at previous meetings in this series. Some key conclusions of the summary session on this topic are cited below (Bhatnagar and Nutt, 2008):

- "Separation of the main heavy metals (U, Pu) and heat bearing components (e.g. Cs, Sr, Am) before disposal increases the repository capacity (3-100 times) in certain geological media.
- The Storage of caesium and strontium for 100-300 years in specialized waste forms is recommended. Because of the long life of Cs-135, after storage, disposal would be required.
- Transmutation/burning of separated MAs (in an ADS or a FR) reduces the 'long-term burden' on repositories. Transmutation of MA has also a favourable impact in the unlikely occurrence of 'human intrusion scenarios'.

Currently, France, Russia, and the United Kingdom operate large reprocessing facilities and Japan is in the process of starting up a substantial reprocessing plant. China and India have smaller facilities that they plan to expand, and the United States has very large reprocessing facility in the planning stage.

The global market for reprocessing has been in the order of 3,000 tHM[3] per year and most of this has been done in three large plants: at La Hague, France, operated by AREVA, at Sellafield, United Kingdom, owned by the UKNDA and, at Mayak/Chelyabinsk, Russia run by Atomenergoprom. A fourth large plant at Rokkasho-mura, Japan, operated by Japan Nuclear Fuel Ltd. (JNFL), is expected to start commercial operation at the end of 2010. The plant capacities La Hague, Rokkasho-mura, Mayak and Sellafield are given in Table 10.1.

The RP&T policies and strategies of many countries are related to international agreements, as described below.

The Generation IV International Forum (GIF, USDOE, 2008), led by the United States, was established in January 2000 to investigate innovative nuclear energy system concepts for meeting future energy challenges. GIF members include Argentina, Brazil, Canada, China, EURATOM, France, Japan, Russia, South Africa, South Korea, Switzerland, United Kingdom, and United States, with the OECD-Nuclear Energy Agency and the International Atomic Energy Agency as permanent observers (GIF, 2008).

[3] tHM is tonnes of heavy metal.

Table 10.1: Major reprocessing facilities with 2007 capacity

Owner/operator	Facility	Capacity in 2007 (tHM/year)
AREVA	La Hague	1,700
JNFL	Rokkasho-mura	800*
Atomenergoprom	Mayak	400
UKNDA	Sellafield	900
Total:		**3,800**

Source: NEA (2008)

Note: * Nominal capacity. Plant start-up was delayed.

Three of the Generation IV reactors are Fast Reactors (FR), of which there are only a few in operation today. These reactors operate with fast neutrons and have no moderator. Present examples use liquid sodium coolant and convert (‘breed’) uranium-238 to plutonium-239 using fuel enriched with 10-20% uranium-235 and plutonium-239. Gen IV is looking at the following three advanced fast reactor designs.

1. Sodium-Cooled Fast Reactor (SFR): a sodium-cooled reactor with fuel recycling, which is an advanced version of today’s FRs.

2. Gas-Cooled Fast Reactor (GFR): helium-cooled, with recycled fuel.

3. Lead-Cooled Fast Reactor (LFR): lead/bismuth eutectic liquid metal coolant and recycled fuel.

There is also an epithermal reactor (Molten Salt Reactor) that could be an FR under certain circumstances, and there are also two advanced thermal neutron reactors in the GIF collaboration, one of which is the focus of Canadian interest.

Canada has had no history in FRs, however, AECL has done some R&D work on a thermal breeder, thorium-cycle reactor based on CANDU. FRs are a possible path to a sustainable closed nuclear fuel cycle with both recycling of fissile materials and burn up of MA, which may significantly reduce the required size of a repository for nuclear fuel waste. RP&T in various forms is an integral component of the GIF program.

Other countries, including Russia, France, Japan, and India are developing advanced nuclear fuel cycles as a means of extending the sustainable lifetime of economical nuclear power production. National and international nuclear energy policy in Europe, France, Japan, and the United States emphasizes sustainability. Sustainability could be achieved in the long term by a fleet of fast reactors, Generation IV and other reactor types, operating with closed nuclear fuel cycles that would both maximize the use of uranium resources and minimize the waste burden on future generations by minimizing the residual amount of long-lived actinides.

At the 2008 NEA P&T meeting in Japan, future energy scenarios were presented by the United States, Japan and Europe describing how this sustainable fission future of fast reactors with closed fuel cycles could be reached starting with reprocessing the fuel from today's light water reactors. Time scales of about 100 years or more were predicted, based on these energy scenarios, to achieve a sustainable fission future. In Canada, which uses a once-through nuclear fuel cycle, sustainability is not a current concern for nuclear power given the country's large uranium reserves.

Achieving the postulated benefit of closed fuel cycles in reducing the volume of used fuel and high-level waste would require the large scale deployment of advanced fast neutron reactors. While three fast reactors are operating and at least two more are under construction, these reactors are primarily experimental and are being used as fuel development tools. Full commercial deployment of closed fuel cycles using fast reactors is still decades away.

Canada's CANDU heavy water reactors use natural uranium fuel and produce a factor of three to five times more spent fuel per unit of electricity produced than light water reactors. However, the amount of space required in a deep geological repository is to a large extent determined by the heat generated by the used fuel, which increases with fuel burnup. As the burnup of the natural uranium fuel is much lower than that of enriched uranium fuel from LWRs, the repository space requirements, dictated by the system thermal performance, would not be expected to be much different on a per-unit-energy basis.

The 2010 watching brief reviewed international developments by examining recent publications and presentations given at the Nuclear Energy Agency information exchange meeting on RP&T (2010, San Francisco). The U.S., several European countries and Japan are in the process of reviewing their RP&T programs. In the U.S., a Blue Ribbon Commission was appointed for the review and will set the future direction of RP&T in their country. Both France and Japan have established 2012 as a major decision point at which time the future direction of these two leading RP&T programs will be decided.

10.1 ALTERNATIVE WASTE MANAGEMENT TECHNOLOGIES

As part of its work program, NWMO is continuing to maintain awareness of the development of alternative approaches for long-term management of used nuclear fuel.

10.1.1 Disposal in Very Deep Boreholes

One of the alternative waste management approaches identified by NWMO for further monitoring is placing the used fuel in very deep boreholes. The concept consists of placing the waste containers at depths of approximately 4 to 6 km in individual boreholes drilled from the surface. The boreholes, up to perhaps one metre in diameter at the bottom, would be lined to allow sequential placement of waste packages one on top of another. With the waste in place, the borehole would be backfilled and sealed. With the waste placed at this depth, further away from the biosphere than in the mined repository concept, the long-term safety of the system would rest primarily on the separation of the hydrogeological regime at the depth of the waste packages from that near the surface, and on the integrity of the borehole plugs and seals.

A 2007 evaluation of the very deep borehole concept for application in the United Kingdom was conducted for the UK Nuclear Decommissioning Authority (Baldwin et al., 2008). In the concept studied, simple packages with no overpack are placed in the lower 2,000 m segment of a borehole drilled from the surface to a depth of 3,000 to 5,000 m. The borehole is fully lined with a metal casing from the surface and of sufficient diameter to ensure ease of placement of the waste packages. Each disposal borehole is drilled either singly, from its own drilling pad, or as part of a group from a central location of limited area. The report identifies several important characteristics of the very deep borehole concept as outlined below.

The concept can result in a small disposal area at depth and to require a relatively small surface area for both the excavation and fuel waste placement operations. It would provide secure disposal of the waste with effectively little chance of recovery. The concept is flexible with respect to implementation in a range of geosphere types. There are, however, uncertainties about the operational procedures for this concept. To date most evaluations have focused on the feasibility of borehole excavation and much less on the operational safety. Limitations in the size of the waste package for practical implementation could mean that the concept will not prove to be efficient for spent fuel.

To date no practical demonstration of the deep borehole concept has taken place, and bringing it to the same level of understanding as the current deep geological repository concepts would require considerable additional R&D. Monitoring of the system and retrieval of the waste would be difficult for the very deep borehole concept compared with the repository approach. There are also serious limitations in those cases where retrievability is considered to be a necessary feature of the system.

Sandia Laboratories has published a preliminary evaluation of the very deep borehole concept for disposal of spent fuel assemblies from the U.S. nuclear power reactors (Brady *et al*, 2009). The report evaluation includes very deep borehole design, cost and schedule, and performance assessment. In this design the waste is assumed to be placed in the bottom 2 km of an approximately 5 km deep borehole drilled through overlying rock into crystalline basement rock. Although retrievability would be maintained during placement operations, retrievability of the waste after borehole sealing is assumed not to be required.

The Sandia evaluation included a costs estimate for a project to place a 109 300 MTHM inventory in 5 km deep boreholes. Construction of a 5 km deep borehole is estimated to take 110 days and to cost about US$20 million. With the assumption that each borehole would contain about 400 fuel assemblies; disposal of the projected 109 300 MTHM inventory in the US would require about 950 boreholes. Assuming a borehole spacing of 200 m, these could be located in several borehole fields totalling about 30 km^2. The construction cost would be about US$19 billion, or 170 000 US$/MTHM. Rough estimates of additional costs, bring total life-cycle cost to US$71 billion (2008 dollars).

A preliminary performance assessment conducted for the concept indicated that ^{129}I was the only radionuclide with a significant concentration reaching the biosphere. The individual peak dose rate was estimated to be 1.4×10^{-12} mSv/a and to occur at 8,200 years from closure of the deep boreholes.

10.1.2 Alternate Approach to the Deep Borehole Concept

Three difficulties attributed to the very deep borehole disposal concept are: 1) that in many designs the waste packages are subjected to high stress because of vertical stacking, 2) that retrievability is questionable, and 3) that long-term monitoring is difficult. A deep borehole system has been proposed (Brunskill and Wilson, 2009) incorporating knowledge from the development of carbon dioxide (CO_2) capture technology, could potentially impose less stress on the waste packages, allowing retrievability and long-term monitoring.

The alternate concept applies to a geological environment in which the hydrological regime is density-stratified to isolate the deeper groundwater system from that nearer the surface. An example of such system could be found in deep sedimentary basins in western Canada, where much of the Precambrian rock surface is covered by several kilometres of sedimentary rock. Te concept consists of a borehole that could be drilled vertically from the surface, through the sedimentary rock, into the Precambrian basement. When into the Precambrian rock a sufficient distance, the hole would then be turned sub-horizontal. Several long, sub-horizontal holes would be used to contain the waste packages. The drilling and completion of the holes could be accomplished with equipment currently used in the petroleum industry in Canada. In the sub-horizontal boreholes the packages would be subjected to less stress than in a vertical configuration. Figure 11.1 illustrates the monitoring of an aquifer above a hypothetical very deep placement borehole using a brine recirculation loop.

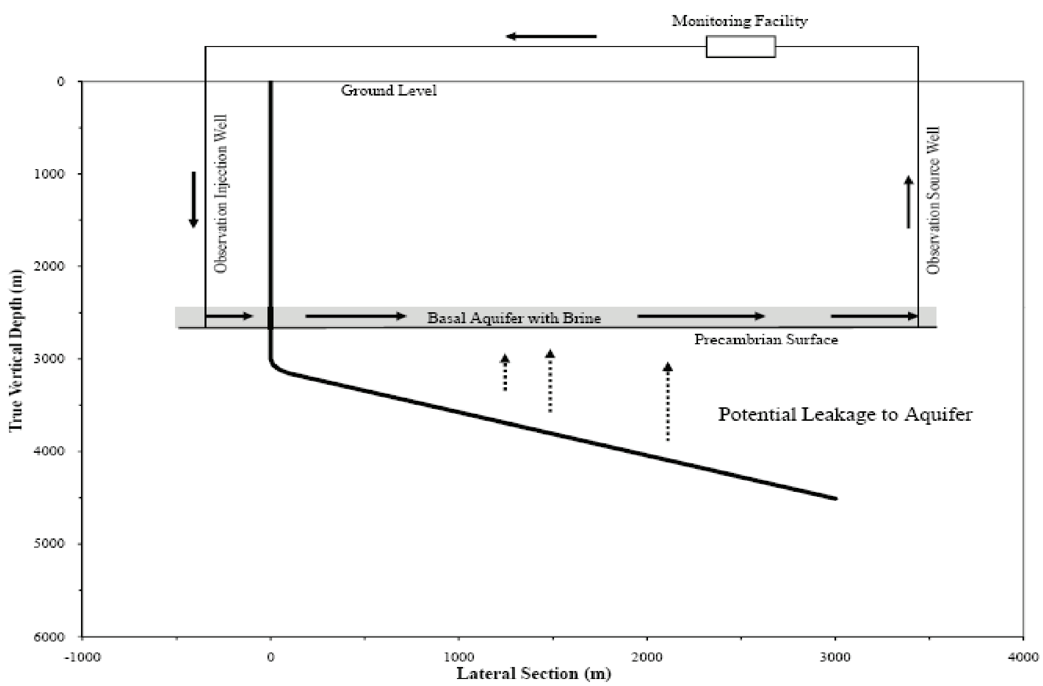

Figure 10.1: Brine circulation-loop in the basal aquifer to monitor leakage into the geosphere.

Work Program **D**

NWMO will continue to monitor developments in alternative waste management technologies.

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