The Role of Rock Engineering in Developing a Deep Geological Repository in Sedimentary Rock

NWMO TR-2008-16 **December 2008**

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ABSTRACT

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Date:	December 2008

Abstract

Rock engineering will play an important role in siting, design, and construction of a deep geological repository (DGR) for nuclear fuel waste in Canada. Post-construction activities such as long-term monitoring, decommissioning, and closure will also require rock mechanics expertise. The type of host rock selected for a DGR will influence the scope of rock engineering activities and related research requirements. Considerable research has been completed on the potential for crystalline rock of the Canadian Shield as a host medium for a DGR. Less information has been compiled for the potential use of sedimentary rock as a host medium. In keeping with the selection of Adaptive Phased Management as the preferred approach for long-term management of Canada's nuclear fuel waste, this report identifies key rock engineering aspects to be considered in advancing the understanding of sedimentary rock as a host medium for a DGR.

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1. INTRODUCTION

The discipline of rock engineering involves the application of rock mechanics and engineering geology principles to resolve engineering issues associated with structures constructed in or composed of rock and possibly other geomaterials. One of the more challenging issues of our time that involves rock engineering is the safe long-term management of used nuclear fuel from nuclear reactors.

Considerable research has been conducted in Canada on concepts to contain and isolate used nuclear fuel in crystalline rock, focused largely on granitic rock of the Canadian Shield. Other countries are considering crystalline rock, volcanic rock, sedimentary rock, and salt as possible host media for a deep geological repository (DGR). A review of used fuel isolation concepts and management strategies (NWMO 2005) recommended that both crystalline rock and sedimentary rock should be considered as potential host media for a DGR in Canada. On June 14, 2007, the NWMO's recommendation was accepted by the Government of Canada.

The life-cycle of a used fuel isolation facility (including a DGR) has two main phases: pre-closure and a post-closure. In the pre-closure phase, the general development stages include siting, design, construction, operation, extended monitoring, decommissioning, and closure/site restoration. Rock engineering plays an important role in each of these development stages. Likewise, there are elements of rock engineering in the post-closure phase related to assessing system performance over an extended period following closure.

The main objective of this report is to provide an overview of the role of rock engineering in the siting, design and construction of a DGR in sedimentary rock. Given that prior comprehensive work related to rock engineering for DGR concepts in crystalline rock has been completed (e.g., Andersson et al., 2000; Martin et al., 2001; and Read and Chandler, 2002), the scope of this report is focused primarily on identifying unique rock engineering aspects related to a DGR in sedimentary rock. Relevant background information is included to clarify the context of the engineering issues. The report is organized in sections covering a general description of the adopted nuclear fuel waste management strategy and DGR conceptual designs; an overview of relevant rock engineering aspects of the three main development stages of a DGR; a review of data requirements and available rock mechanics data, tools and techniques; a discussion of findings; and conclusions and recommendations.

2. LONG-TERM NUCLEAR FUEL WASTE MANAGEMENT IN CANADA

2.1 ADAPTIVE PHASED MANAGEMENT

The NWMO is implementing Adaptive Phased Management and collaboratively developing with Canadians the process to site a deep geological repository for nuclear fuel waste. Adaptive Phased Management will proceed in phases. From a technical perspective, following the launch of the siting process, the initial phase will likely involve feasibility studies and preliminary investigations at potential sites in volunteer communities, followed by more detailed site investigations to confirm whether the candidate sites have the geological and other characteristics required to safely host a repository. Following selection of a preferred site and the necessary environmental assessment and licence approval process, an underground characterization facility (UCF) would be constructed and site-specific research and technology demonstration would be performed. During this period, in-situ characteristics of the site at repository depth would be obtained and the final design and safety assessments would be prepared prior to final construction and operation of the repository.

3. TECHNICAL ASPECTS OF A DEEP GEOLOGICAL REPOSITORY (DGR)

3.1 TECHNICAL FACTORS FOR SITING A DGR

The central facility for the shallow rock cavern, UCF, and DGR is to be located in a suitable rock formation such as the crystalline rock of the Canadian Shield or the Ordovician sedimentary rock basins. These two rock types cover large portions of several provinces and territories.

The rationale for including both the crystalline rock of the Canadian Shield and Ordovician sedimentary rock as potentially suitable host rock formations for a DGR was based on the following information (NWMO, 2005):

- The 1977 Hare report identified several potentially suitable rock types in Canada for a DGR for used nuclear fuel that included salt, crystalline rock, sedimentary rock and volcanic tuff. The report indicated that the Canadian repository research and development (R&D) program should study several different rock types but that resources should not be spread too thinly, focusing primarily on crystalline rock while monitoring work being conducted in other countries on other rock types.
- Since 1978, the crystalline rock in the Canadian Shield has been the primary focus of the Canadian repository R&D program, including development of the Underground Research Laboratory (URL) by AECL near Lac du Bonnet, Manitoba. The potential suitability of the crystalline rock of the Canadian Shield for a DGR has been described in AECL's 1994 Environmental Impact Statement (EIS) (AECL, 1994) and associated geoscientific and safety assessment reports. There also exists extensive documentation of the potential suitability of crystalline rock as a host medium for a DGR in other countries such as Sweden, Finland and Switzerland.
- Since the 1980's, a limited number of Canadian studies have been undertaken on the potential for sedimentary rock as the host medium for a DGR (e.g., Mazurek, 2004). These studies indicate that sedimentary rock formations are relatively wide-spread in the provinces of interest, have favourable geotechnical properties, relatively simple structure, and are homogeneous and thick. Ordovician sedimentary rock formations (age 470 to 430 million years) can be found in Canada at sufficient depth below surface and have sufficient thickness to meet technical siting criteria for a DGR. Several countries including Switzerland, France, Spain and Japan are studying both crystalline rock and sedimentary rock in their repository programs.
- From a geoscientific perspective, sedimentary rock formations such as the Ordovician have low hydraulic conductivity, resulting in very slow movement of groundwater in the formations, with the migration of dissolved material dominated by diffusion. Furthermore, sedimentary formations comprising clay may be capable of self-sealing fractures and faults, and the clay minerals tend to retard migration of many dissolved minerals through a process of adsorption.
- In 2004, a high-level review commissioned by the NWMO to identify implications of siting a DGR for used nuclear fuel in Ordovician sedimentary rock found that

construction of a DGR in sedimentary rock is feasible and that the costs would be similar or less than a DGR constructed in crystalline rock (RWE-NUKEM, 2004b,c).

Several independent geoscientific studies suggest that Ordovician shales and limestones may provide a suitable environment to host a DGR for used nuclear fuel in Canada (NWMO, 2005). Other sedimentary rock formations may also be potentially suitable to host a repository. Like the Canadian Shield granite, the Ordovician sedimentary rock basins are naturally occurring geological formations characterized by long-term stability, relatively high rock strength, and low groundwater flow. Suitable horizons within these formations that occur at sufficient depth below ground surface, and lack mineral resources, are highly unlikely to be disturbed by erosion or accidental drilling. However, further research is required to prepare a safety case for a DGR in a host medium other than the crystalline rock of the Canadian Shield. Furthermore, the results from detailed site specific characterization activities obtained during the site investigation, site selection and licensing phase would be required to confirm the technical suitability of any host rock formation for a DGR.

Figure 1 presents a conceptual view of a DGR.

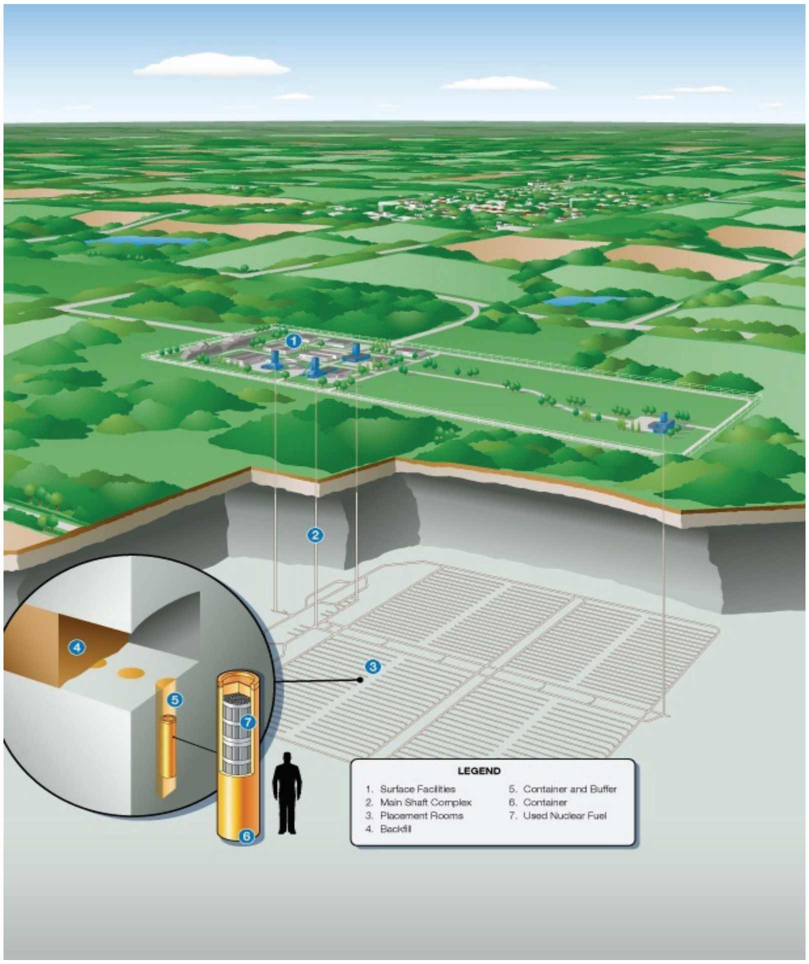

Figure 1: Conceptual View of a Deep Geological Repository

3.2 CONCEPTUAL DGR DESIGNS

Various DGR designs have been advanced in Canada and other countries since the submission of AECL's EIS in 1994. Conceptual DGR designs were reviewed as part of a study on the potential for rock fracturing related to DGR development (Read 2008). Four of the designs that have been investigated for possible application in Canada are as follows:

- AECL-type in-room placement design (CTECH, 2002; Baumgartner and Ates, 2002; Baumgartner et al., 1996).
- KBS-3V-type in-floor borehole placement design (RWE-NUKEM, 2004; Birgersson et al., 2001; Simmons and Baumgartner, 1994).
- KBS-3H-type in-room placement design (Lindgren et al., 2003).
- NAGRA-type in-room placement design (NAGRA, 2002).

3.2.1 AECL-type In-Room Placement Design

The original AECL-type in-room placement design is summarized in Appendix A. The refined conceptual in-room placement design (CTECH, 2002) for a DGR includes the following features:

- Four vertical shafts ranging from 3.66 to 7.30 m internal diameter connect the repository level to ground surface. This design has only one upcast exhaust ventilation shaft compared to the original AECL design with two exhaust shafts.
- The repository level (Figure 2) comprises room-and-pillar excavations, including twinned central and section access tunnels connected to a perimeter access tunnel. These access tunnels are rectangular (4.2 m high by 7.0 m wide) with an arched back. The twinned central and section access tunnels divide the repository into four sections, each section containing two panels of placement rooms. The twinned access tunnels are spaced 50 m centreline-to-centreline.
- Each placement panel comprises 13 elliptical placement rooms (4.2 m high by 7.14 m wide) with single-ended access. Placement rooms are oriented parallel to the maximum principal stress direction to minimize stress concentrations around the underground openings. Individual placement rooms are 315 m long, including a 37 m segment to accommodate a sealing bulkhead and turning radius of 25 m. Placement rooms are spaced a minimum of 45 m centreline-to-centreline from one another and about 60 m from the perimeter access tunnels. There is a minimum distance of 22.7 m between ends of placement rooms in adjacent panels in a given section.
- Within each room, the used fuel container (UFC) spacing is 5.13 m centre-to-centre longitudinally along the room, with two parallel rows of UFCs spaced 2.52 m laterally across the room (Figure 3). The UFCs are located in a mass of pre-compacted buffer and dense backfill blocks, and associated sealing materials and structures. A minimum thickness of 0.5 m of bentonite/buffer and another 0.5 m of dense backfill is required around each container. Each placement room can accommodate 108

containers (two abreast by 54 along the room) for a total repository capacity of 11,232 UFCs (or 3,639,168 used-fuel bundles). The maximum surface temperature of the UFCs in this arrangement is 97°C, reached 16 years after placement.

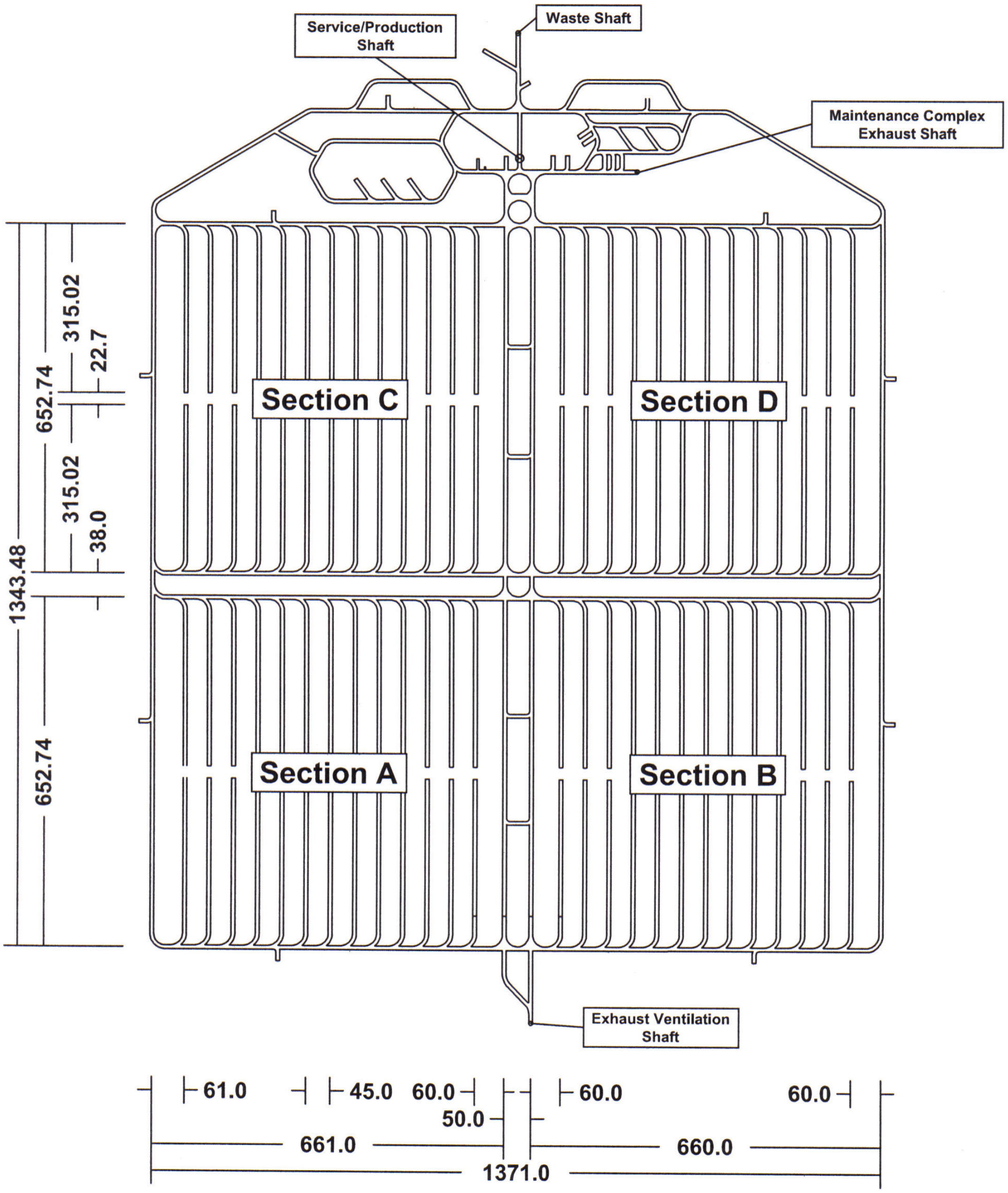

Figure 2: In-Room Placement Design of the DGR (CTECH, 2002)

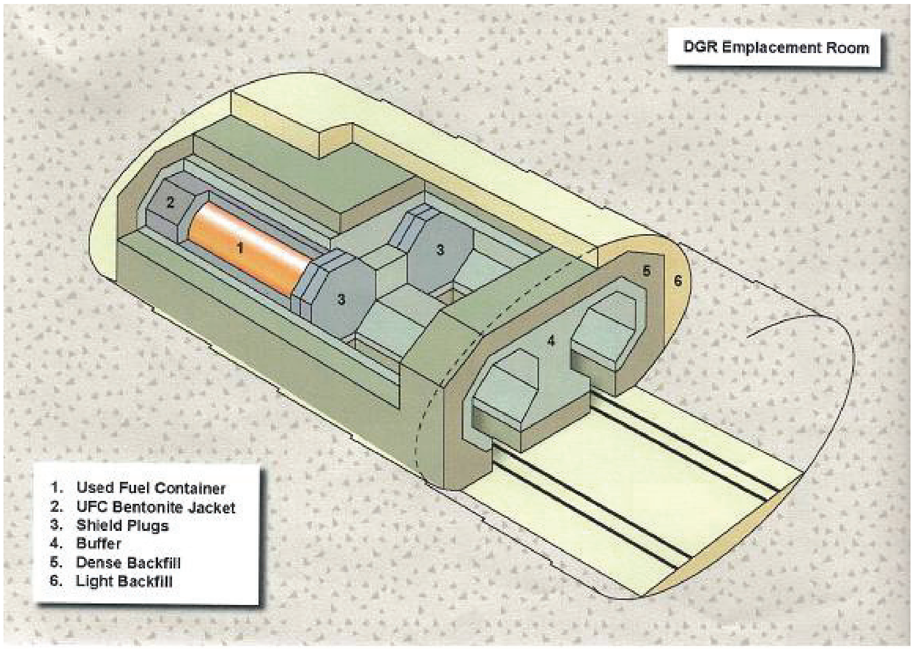

Figure 3: Typical Placement Room in the In-Room Placement Design (CTECH, 2002)

- The placement area in this conceptual design is 1358 m by 1343 m based on ideal site conditions (i.e., assuming no adaptation required to accommodate unfavourable geological structures or conditions in the rock mass). The actual layout and size of the repository will depend on in situ conditions encountered at a selected repository site. At a target placement rate of 120,000 fuel bundles/year, the repository is assumed to have an operational life of 30 years.
- Once filled, each placement room is sealed with a 12 m long concrete bulkhead. Monitoring of seals and conditions in the repository is planned to continue for an extended period of time during which access tunnels and shafts will remain open. Following this monitoring period, decommissioning of the DGR involves removing all underground support works, and backfilling and sealing the balance of the underground facilities.

3.2.2 KBS-3V-type In-floor Borehole Placement Design

Following completion of the revised conceptual in-room placement design, a DGR design that incorporates placement of UFCs within boreholes constructed in the invert of placement rooms was further examined (RWE-NUKEM, 2003; 2004). The original AECL concept for this conceptual design is summarized in Appendix A. The revised conceptual design (Figure 4) incorporates features required for in-floor placement based on the Swedish KBS-3V design (Birgersson et al., 2001). It utilizes some of the key features of the conceptual in-room placement design (CTECH, 2002). The main points of comparison between this design and the in-room design are as follows:

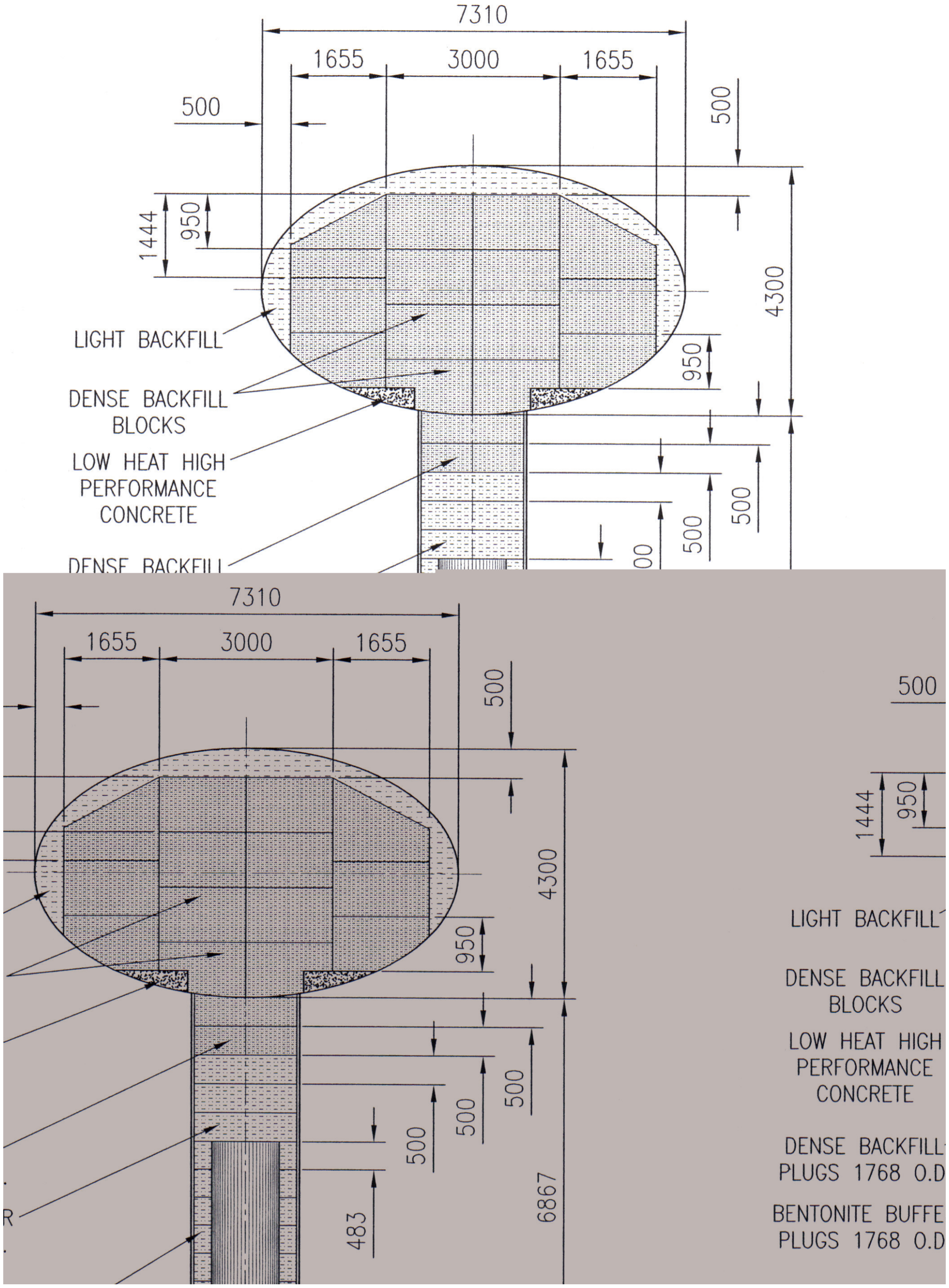

Figure 4: In-Floor Placement Concept (RWE-NUKEM, 2003)

- The shafts and repository level are similar to those in the in-room design. The twinned central and section access tunnels divide the repository into four sections, each section containing two panels of placement rooms. The twinned access tunnels are spaced 50 m centreline-to-centreline.
- Each placement panel comprises 20 elliptical placement rooms (4.3 m high by 7.31 m wide) with single-ended access. Placement rooms are oriented parallel to the maximum principal stress direction to minimize stress concentrations around the underground openings. These room dimensions are dictated by the size of equipment required to drill the boreholes and to place a UFC in a borehole. Individual placement rooms are 325 m long, including a 37 m segment to accommodate a sealing bulkhead and turning radius of 25 m. Placement rooms are spaced a minimum of 30 m centreline-to-centreline from one another, and a minimum of 50 m from the perimeter access tunnel. There is a minimum distance of 50 m between ends of placement rooms in adjacent panels in a given section.
- Within each room, vertical boreholes are drilled along the centreline of the room, spaced 4.0 m centre-to-centre. Each borehole is 1.868 m diameter drilled to a depth of 6.867 m below the lowest point in the excavated room (or 7.323 m below the top of the concrete floor in the room). The borehole is filled with one pre-compacted bentonite buffer plug and eight pre-compacted bentonite buffer rings prior to UFC placement. Three more buffer plugs and two dense backfill plugs are placed above the UFC to seal the borehole, then pre-compacted dense backfill blocks and light backfill are placed to seal the room.
- Each placement room can accommodate 70 containers for a total repository capacity of 11,200 UFCs (or 3,628,800 used-fuel bundles). The maximum surface temperature of the UFCs in this arrangement is 79°C after 29 years, and 90°C after 6500 years (assuming an initial ambient temperature of 17°C).
- The placement area in this conceptual design is 1390 m by 1450 m based on ideal site conditions. The repository is assumed to have an operational life of 30 years based on a target placement rate of 120,000 fuel bundles/year.
- Once filled, each placement room is sealed with a 12 m long concrete bulkhead keyed into the rock mass and grouted to seal the excavation damaged zone (EDZ). Monitoring of seals and conditions in the repository is planned to continue for an extended period of time during which access tunnels and shafts will remain open. Following this monitoring period, decommissioning of the DGR involves removing all underground support works, and backfilling and sealing the remaining underground facilities.

3.2.3 KBS-3H-type Horizontal Borehole Placement Design

In addition to the revised conceptual design for in-floor placement of UFCs, a DGR design that incorporates placement of UFCs within long horizontal boreholes constructed from niches off of the DGR access tunnels was investigated (RWE-NUKEM, 2004a). With reference to Figures 5 and 6, this revised conceptual design incorporates features based on the Swedish KBS-3H design (Thorsager and Lindgren, 2004). It utilizes some of the features of the conceptual in-room placement design (CTECH, 2002). The main points of comparison between this design and the in-room design are as follows:

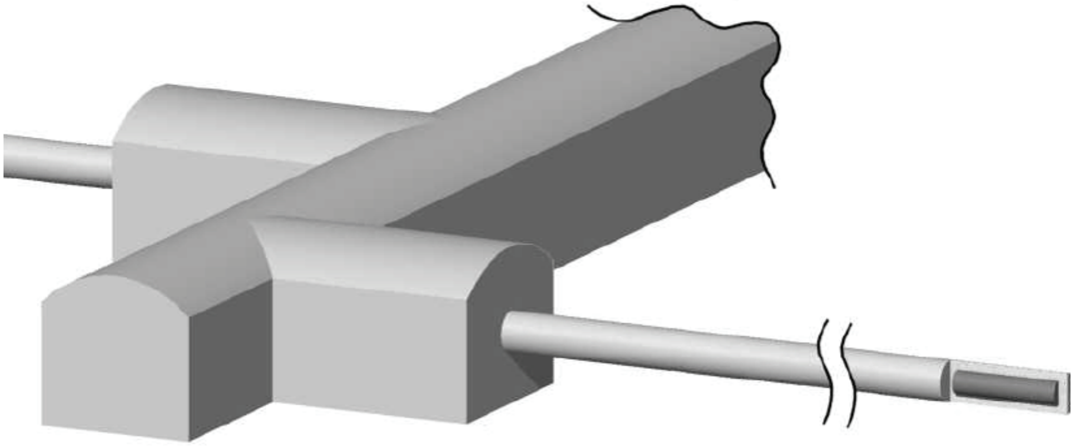

Figure 5: KBS-3H Concept for Placement of UFCs in Long Horizontal Boreholes (unpublished source)

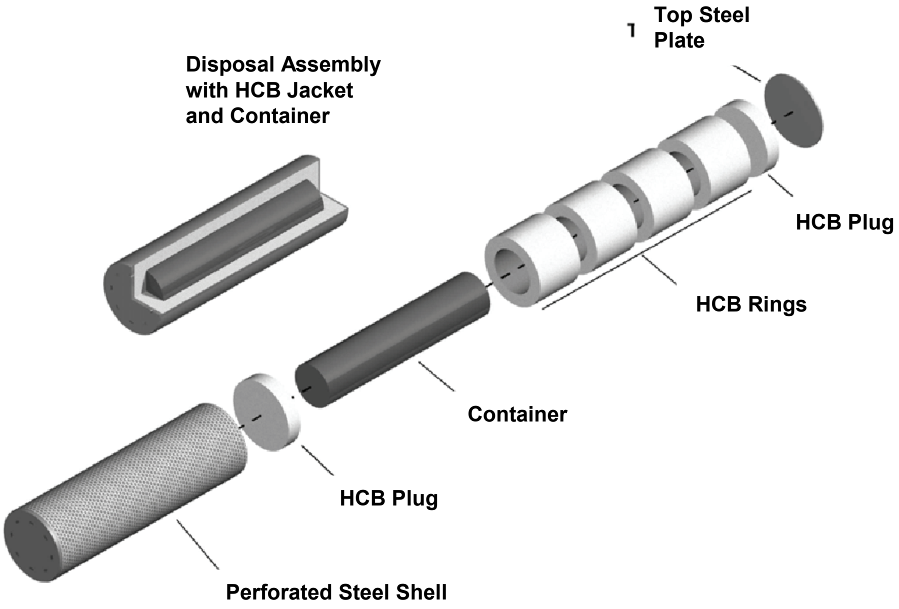

Figure 6: KBS-3H Concept for an Encapsulated UFC (unpublished source)

- The shafts and repository level are similar to those in the in-room design. The twinned central and section access tunnels divide the repository into six sections, each section containing two panels of placement boreholes. The twinned access tunnels are spaced 50 m centreline-to-centreline.
- Each placement panel comprises 18 circular placement boreholes (1.918 m diameter) with single-ended access, inclined 5° upward to promote drainage. Borehole diameter is dictated by the minimum thickness of bentonite buffer around the container and equipment/operational consideration for placement of UFCs. Placement boreholes are oriented parallel to the maximum principal stress direction to minimize stress concentrations around the underground openings. Individual placement boreholes are 297.2 m long drilled from a 33 m long niche off of the section access tunnels (comprising an 8 m long straight section and a 25 m long section with a 25 m turning radius). Placement rooms are spaced a minimum of 55 m centreline-to-centreline from one another, and a minimum of 50 m from the perimeter and central access tunnels. There is a minimum distance of 25.6 m between ends of placement boreholes in adjacent panels in each section.
- Each UFC is encased within a bentonite jacket with a nominal thickness of 300 mm, which is in turn surrounded by a perforated carbon steel cage to prevent damage during handling and placement. There is an initial 50 mm thick annular air gap left around the placed UFC package, although the package may sit eccentrically on the bottom of the borehole. Within each borehole, UFCs are spaced 5.6 m centre-to-centre with a bentonite plug separating individual UFC packages. This design accommodates 52 UFCs per hole, providing a total repository capacity of 11,232 UFCs (or 3,639,168 used-fuel bundles). The maximum surface temperature of the UFCs in this arrangement is 94°C, reached three years after placement.
- The placement area in this conceptual design is 2120 m by 2158 m based on ideal site conditions, assuming no adaptation required to accommodate unfavourable geological structures or conditions in the rock mass. The actual layout and size of the repository will depend on in situ conditions encountered at an actual repository site. At a target placement rate of 120,000 fuel bundles/year, the repository is assumed to have an operational life of 30 years.
- Once filled, each placement borehole is sealed with a 6 m long concrete bulkhead. Monitoring of seals and conditions in the repository is planned to continue for an extended period of time during which access tunnels and shafts will remain open. Following this monitoring period, decommissioning of the DGR would involve removal of all underground support works, and backfilling and sealing remaining underground facilities.

3.2.4 NAGRA-type In-Room Placement Design

To complement the other revised conceptual designs for placement of UFCs, a DGR design that incorporates placement of UFCs within long horizontal cylindrical tunnels was investigated (RWE-NUKEM, 2004b). This revised conceptual design (Figure 7) incorporates features based on the NAGRA disposal concept (NAGRA, 2002). It utilizes some of the features of the conceptual in-room placement design (CTECH, 2002). The main features of this design are as follows:

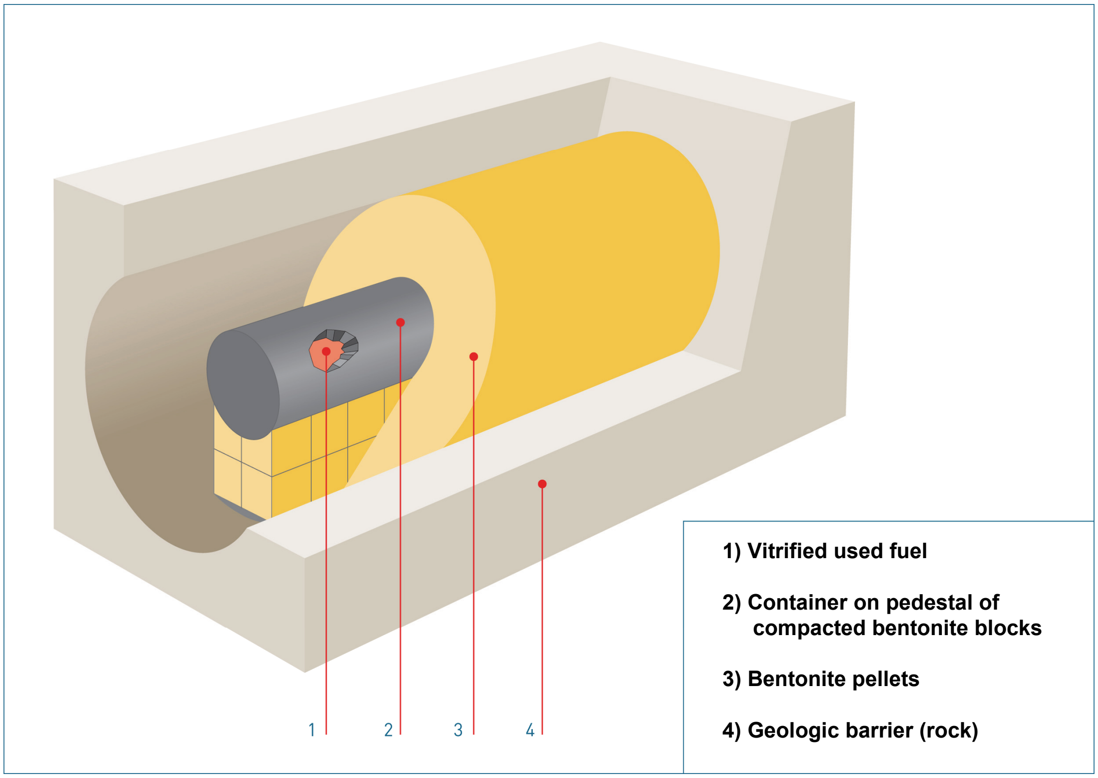

Figure 7: NAGRA Placement Concept in Horizontal Circular Tunnels (NAGRA website)

- The shafts and repository level are similar to those in the in-room design. The twinned central and section access tunnels divide the repository into four sections, each section containing one panel of placement rooms. The twinned access tunnels are spaced 50 m centreline-to-centreline.

- Each placement panel comprises 25 placement tunnels (2.5 m diameter) with double-ended access. Placement tunnels are oriented parallel to the maximum principal stress direction to minimize stress concentrations around the underground openings. Individual placement tunnels are 820 m long excluding the 45 m long curved access drift extension at each end of the tunnel. Placement tunnels are spaced a minimum of 40 m centreline-to-centreline from one another, and a minimum of 50 m from the perimeter and central access tunnels.

- Each UFC is placed on a compacted bentonite block pedestal within the placement tunnel and the remainder of the tunnel is filled with compacted bentonite pellets. This arrangement creates a 666-mm-thick bentonite buffer ring around the placed UFC. Within each tunnel, UFCs are spaced 6.9 m centre-to-centre. This design accommodates 112 UFCs per tunnel, providing a total repository capacity of 11,200 UFCs (or 3,628,800 used-fuel bundles). The placement area in this conceptual design is 1870 m by 2170 m based on ideal site conditions. The repository is assumed to have an operational life of 30 years assuming a target placement rate of 120,000 fuel bundles/year.

- Once filled, each placement borehole is sealed with a 20 m long bentonite seal (consistent with the NAGRA approach). Monitoring of seals and conditions in the repository is planned to continue for an extended period of time during which access tunnels and shafts will remain open. Following this monitoring period, decommissioning of the DGR would involve removing all underground support works, and backfilling and sealing remaining underground facilities.

3.3 OTHER TECHNICAL CONSIDERATIONS

3.3.1 Construction and Operation

Adaptive Phased Management includes an optional step of shallow underground storage of used fuel at the repository site while awaiting development of the DGR. Storage containers at a central underground storage facility are based on the existing design of the dry storage container or equivalent with a 100-year design life, and placed in a series of shallow rock caverns excavated at a nominal depth of 50 m below surface.

The interim optional storage concept in shallow rock cavities is similar in some respects to that being employed in Sweden at the CLAB facility near the Aspö Hard Rock Laboratory (Figure 8). Adaptive Phased Management is based on a multi-barrier approach to contain and isolate used nuclear fuel in a DGR. Containers for long-term isolation in a DGR are based on a 100,000-year design life. These durable containers are designed to withstand long-term environmental effects such as climate change and glaciation. Facilities would exist at the central site to repackage the used fuel. During the long-term isolation period, used fuel would be placed in a network of horizontal access tunnels and rooms excavated in stable rock at a depth of about 500 m below surface. It should be noted that the final depth of the DGR will be influenced by site conditions and other factors. Used fuel containers would be placed within the rooms or in boreholes drilled into the floor of the rooms. Clay-based materials would be used to surround and protect the containers, to fill the void spaces in the repository, to limit the movement of groundwater and dissolved material, and to protect workers during container placement operations. These sealing systems would involve materials such as high-performance concrete and swelling bentonite clay.

Construction considerations include the excavation methods to be employed, design and installation of underground tunnel support, sequencing of operations, equipment selection, ventilation, dust control, and other generally understood construction aspects. Operational considerations include adequate thermal and radiological buffering and proper sequencing of operations to avoid unnecessary impacts to personnel or the environment.

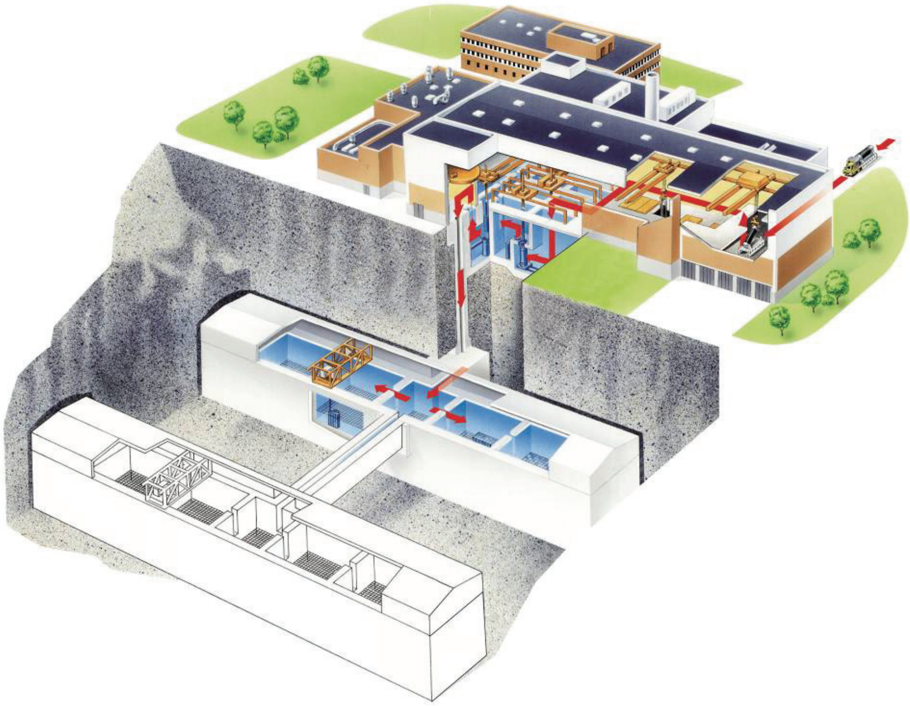

Figure 8: SKB's CLAB Interim Storage Facility at Oskarshamn (SKB photo archives)

3.3.2 Monitoring

As part of the Adaptive Phased Management approach, used fuel would be monitored in the optional central shallow rock caverns and in the DGR. Monitoring would be relatively straightforward over the interim storage period as the storage containers would be readily accessible. During the extended monitoring period following placement of used fuel containers in the repository, monitoring would require considerably more effort and reliable technology since the long-term isolation containers would be backfilled and sealed within the placement rooms. The purpose of monitoring is to confirm the long-term safety and performance of the repository system. Until a decision is made to backfill and seal the access to the DGR, monitoring would take place in situ at repository depth. After closure of the deep repository, post-closure monitoring of the facility could take place from ground surface, and in boreholes drilled from surface.

3.3.3 Retrieval

As part of the concept, used fuel would be retrievable at all times. The technology to retrieve used fuel containers from a DGR would need to be further developed and demonstrated at the site. Used fuel retrieval from interim storage would be straightforward given that the storage containers are readily accessible. However, during the extended monitoring period, used fuel retrieval would require more effort and specialized technology because the long-term isolation containers would be backfilled and sealed within the placement rooms.

3.3.4 Decommissioning

Once a societal decision is made and the necessary approvals obtained, decommissioning would commence and all underground access tunnels and shafts would be backfilled and sealed. Surface facilities would be decontaminated and dismantled. Closure activities would include removal of monitoring instruments. Upon closure, the design and function of permanent site markers is a long-term consideration.

4. ROCK ENGINEERING ASPECTS OF DGR DEVELOPMENT

Rock engineering considerations and issues with respect to development of a DGR in crystalline rock have been investigated in Canada, Sweden and other countries. In addition to NWMO (2005), three publications that provide a detailed description in this regard are used as the primary reference basis for the following sections. These reports are summarized below:

- Andersson et al. (2000) provide a summary of geoscientific suitability indicators and criteria for siting and site evaluation in Sweden, with particular emphasis on host rock requirements for a KBS-3 repository. Based on SKB's experience over many years of research and development, the report details required and preferred characteristics and conditions in the rock, and criteria to be used to identify potential candidate sites and during site investigation at each candidate site. The reported requirements, preferences and criteria provide the technical basis for SKB's site selection process and site investigations.

  The results, and particularly the stipulated criteria, apply to a KBS-3 repository for used fuel, where the fuel is contained in copper canisters embedded in bentonite clay at a depth of 400 to 700 m in the Swedish crystalline basement. If the repository concept is changed or if new technical/scientific advances are made, certain requirements, preferences or criteria may need to be revised. The authors emphasize that the findings of the report cannot be used directly as a basis for siting other types of repositories, or in other geological settings.

- Martin et al. (2001) synthesize important rock mechanics findings from the Canadian and Swedish research programs and identify their relevance in assessing the stability of underground openings. The report draws heavily on published results from SKB's ZEDEX Experiment in Sweden (Olsson et al., 1996) and AECL's Mine-by Experiment in Canada (Read and Martin, 1996), and incorporates examples from mining and tunnelling to illustrate the application of these findings to underground excavations in general.

  The report describes, using the current state of knowledge, the role rock engineering can play in siting and constructing a KBS-3 repository. The key rock mechanics parameters to be determined in order to facilitate repository siting and construction in crystalline rock are identified. Possible construction issues associated with rock stability that may arise during excavation of underground openings of a KBS-3 repository are discussed. The report provides a convenient reference document for the major rock mechanics issues to be addressed during the siting, construction and closure of a nuclear waste repository in hard crystalline rock in Sweden.

- Read and Chandler (2002) present findings of the Thermal-Mechanical Stability Studies, a comprehensive multi-disciplinary research project conducted in Canada between 1996 and 2001. The authors describe the main objectives of excavation design for a nuclear waste repository as follows: 1) to create stable underground openings capable of withstanding the thermal-mechanical loading history expected over the lifetime of the repository, and 2) to minimize excavation damage. The objective of the Thermal Mechanical Stability Studies was to develop a suite of engineering tools and techniques to facilitate design of stable repository excavations with minimal excavation damage.

  The project advanced the state of knowledge in a number of areas including numerical modeling of progressive failure and damage development around underground openings using the Particle Flow Code (PFC)[1] and other micro-mechanical models, monitoring rock mass response to excavation using conventional instruments in conjunction with acoustic emission/microseismic (AE/MS) monitoring technology and methods, and characterizing rock properties and rock mass response under ambient and elevated temperature through specialized in situ and laboratory characterization and testing methods. The role of thermoporoelastic response of the rock mass and pore pressure analyses in rock mass stability calculations were also assessed.

  Read and Chandler (2002) summarize the findings from the Thermal Mechanical Stability Studies in the context of DGR rock mechanics studies, and assess the state-of-the-art in repository excavation design tools and capabilities. They also establish a systematic design approach that integrates characterization, monitoring, and numerical modeling tools and capabilities into an engineering system for back analysis and forward prediction of short- and long-term rock mass responses, and associated changes in material properties. Although the focus of the report is a DGR in crystalline rock in Canada, many of the findings are applicable to other host rock environments and applications.[2]

These reports are referred to extensively in the remainder of this document. Other publications and reports providing additional information are also referenced in the following sections.

4.1 SITING

The technical aspects of the siting process are intended to help identify candidate sites for a DGR and containment facility. To proceed, specific siting criteria are required to identify potential candidate regions, candidate areas within these regions, and then specific candidate sites within these areas (see for example AECL, 1994). The process of narrowing the search for a preferred candidate site requires both technical and non-technical data and information. A

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[1] Particle Flow Code - commercial software from HCItasca, 111 Third Avenue South, Suite 450, Minneapolis, MN 55401, USA

[2] 'Rock Mechanics Results from the Underground Research Laboratory, Canada' was the topic of a special issue of the International Journal of Rock Mechanics and Mining Sciences, Volume 41 (8), December 2004. Chandler, N., R. Guo, and R. Read (Guest Editors). It summarizes key findings from the Thermal Mechanical Stability Studies and related work.

Figure 9: Surface Characterization in Limestone (Southern Alberta)

subset of the siting criteria includes exclusion criteria – specific conditions or features upon which a particular site is excluded from further consideration. As with the general siting criteria, factors both technical (e.g., rock mass conditions) and non-technical (e.g., social) are taken into account.

The primary role of rock engineering at this stage of DGR development is to define preliminary surface and subsurface conditions and characteristics of the geosphere. The characteristics of the bedrock must promote long-term safety of the DGR, and a safe working environment that meets occupational health and safety regulations (Martin et al., 2001). Other aspects, such as site access feasibility, are secondary considerations. The relevant rock engineering issues associated with surface and subsurface characterization are described in the following subsections. Figure 9 shows an example of characterizing major surface fractures in limestone.

4.1.1 Surface Characterization

The purpose of surface characterization is to develop an understanding of the physiographic setting of regions and areas that may contain candidate sites. The collected information is used to help identify potentially suitable areas that may contain candidate sites. Equally important is delineating areas to be excluded from further investigation on the basis of technical or non-technical considerations. Andersson et al. (2000) describe the following Swedish exclusion criteria related to surface conditions in potential study areas in crystalline rock:

- After completion of a feasibility study, continued studies and investigations are conducted only in areas deemed to have no potential for occurrence of ore or valuable industrial minerals, deemed to be homogeneous, and deemed to consist of commonly occurring rock types.

- During the feasibility study, the site to be investigated is selected and adapted so that a deep repository can be positioned with good margin in relation to regional plastic shear zones and regional fracture zones interpreted in the feasibility study. If it can be shown conclusively that a repository cannot be accommodated by the projected structural geology, the site is not considered further.
- Areas protected by law are to be avoided, and areas for further investigations are to be chosen so that they have few conflicting interests (for example a water source) and can be adapted with little impact on the near-surface ecosystem. Areas where biological diversity or species worth protecting may be threatened, and areas which are or may be important water sources, soil sources or farmland, are to be avoided for the deep repository's surface facilities.
- Areas with an unsuitably high topographic gradient on a regional scale (greater than 1%) are to be rejected.

The first three of these criteria are considered reasonable for the siting process in sedimentary rock, although the projection of structural geological features and identification of horizons of potentially valuable ore or minerals may not be possible without subsurface investigation (see Section 4.1.2). The last of these criteria would require further study, as the layered nature of sedimentary rock and possible presence of regional aquifers and aquitards may negate or marginalize the effects of surface topography.

To facilitate surface characterization of an area, or a site within an area, Andersson et al. (2000) identify the following preferences with respect to surface conditions:

- A high proportion of exposed rock and otherwise moderate soil depth (preferably less than about 10 m) to facilitate determination of the lithological and geological-structural conditions in the underlying bedrock from the ground surface.
- Homogeneous bedrock with few rock types and regular fracturing, although small-scale variation in mineral composition (e.g., gneiss) is not considered significant.

These criteria are based on crystalline rock conditions in Sweden. From a practical perspective, the first preference is reasonable but not essential. The second preference requires modification for sedimentary rock as this type of rock is, by its nature, stratified and may exhibit large variations in lithology and structural geology between stratigraphic layers. Moreover, the degree of homogeneity of a potential repository horizon in sedimentary rock cannot be determined from surface characterization unless it outcrops at some distance from the investigation area.

Surface characterization studies are conducted using a variety of standard tools and techniques. Data sources such as air photos, surficial geology maps, bedrock geology maps, topographic maps, mining-related maps, and seismic and climate records provide the basis for desktop studies. The objective of these studies is to develop a general understanding of near-surface and surficial geology, terrain type, geomorphological features, topography, and seismic conditions of an area, and their relation to other features such as waterbodies, and population centres. Alone or in combination with subsurface information from non-intrusive investigation techniques, this information is used to identify potential exclusion areas and areas where subsurface investigation is warranted. Information gathered from climate records and seismic records provides a preliminary basis for estimating potential boundary conditions that may affect a particular area, or sites within an area.

New technology such as LiDAR (Light Detection And Ranging) is ideal for developing detailed digital elevation models (DEMs) of the ground surface. These 3D models can be used in a GIS environment as a base for draped orthophotography to develop detailed representations of surface conditions. Other features such as bare earth modeling and hill-shading are useful tools for identifying potentially important features such as faults, landslides, subsidence areas, and sinkholes in karst terrain that may represent significant geohazards. Karst development (i.e., bedrock dissolution) in limestone and anhydrite horizons is a unique phenomenon specific to sedimentary rock. The features identified in a desktop study may affect the suitability of a site for a DGR, a shallow interim storage facility, or access to the site.

Field reconnaissance is a subsequent step in the surface characterization process to conduct geological/geotechnical mapping of surface exposures and collect samples of outcrop materials for possible mechanical, hydraulic and chemical testing. Rock mass classification is undertaken on the basis of the collected information. This field activity also provides opportunity to identify artesian (springs) and surface drainage conditions. On a regional scale, confirmation of a particular area as a recharge or discharge area for groundwater flow is an important objective of this stage of the characterization process, although as mentioned previously, the influence of topography in sedimentary rock requires further study.

Although many of these considerations overlap with the fields of geology, hydrogeology, geography and soil mechanics, a comprehensive multi-disciplinary approach to surface characterization requires a central role of rock engineering and engineering geology to ensure technical information is assessed within an appropriate geotechnical/geomechanical framework.

4.1.2 Subsurface Characterization

Subsurface characterization of the geosphere is a critical activity to define rock mass conditions that may affect suitability for a DGR. This process involves intrusive and non-intrusive exploration techniques. Examples of intrusive techniques include core drilling and exploratory shaft excavation, as well as underground investigations during development of the shallow interim storage facility and UCF at the preferred site. Non-intrusive techniques include airborne and ground geophysics using a variety of geophysical tools (e.g., gravimetric, reflection and refraction surveys). Downhole logging tools are also essential at this stage to measure in situ properties of the rock mass for comparison with properties derived from core testing, and for confirming fracture characteristics. Caliper measurements and observations of borehole breakouts are also useful in determining in situ stress conditions.

Andersson et al. (2000) identify the following requirements and exclusion criteria with respect to bedrock or the placement of the DGR within bedrock:

- The rock in the repository deposition zone must not have any ore potential (i.e. must not contain such valuable minerals that it might justify mining at repository depth). If large deposits of ore-bearing minerals or valuable industrial minerals are encountered within the repository area, the site is to be abandoned.
- Regional plastic shear zones are to be avoided if it cannot be demonstrated that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be so-called tectonic lenses near regional plastic shear zones where the bedrock is homogeneous and relatively unaffected.

- It must be possible to position the repository with respect to the fracture zones on the site. Deposition tunnels and deposition holes for canisters must not pass through or be positioned too close to major regional and major local fracture zones. Deposition holes must not intersect identified local minor fracture zones. During site investigation, suitable respect distances to major identified regional and local major fracture zones must be maintained. A distance of at least several tens of metres to major local zones and at least 100 m to regional zones is considered appropriate. If the repository cannot be positioned in a reasonable manner (i.e., if it would have to be split up into a very large number of parts) in relation to regional plastic shear zones, regional fracture zones or local major fracture zones, the site is not suitable for a deep repository.

- The rock strength, fracture geometry and initial stresses must be such that large stability problems will not arise around tunnels or deposition holes within the deposition area. This is checked by means of a mechanical analysis, where the input values comprise the geometry of the tunnels, the strength and deformation properties of the intact rock, the geometry of the fracture system and the initial rock stresses. If the repository cannot be reasonably configured in such a way that extensive and general stability problems can be avoided, the site is unsuitable and should be abandoned. Extensive problems with discing of drill cores should be considered an indication that such problems may arise.

- The groundwater at the repository level must not contain dissolved oxygen. Absence of oxygen is indicated by a negative Eh, occurrence of Fe(II), or occurrence of sulphide. At least one of these indicators must be evident in measurements of groundwater composition at repository depth. If none of these indicators are evident, a more thorough chemical assessment is required. If these further studies do not confirm oxygen-free conditions, the site is to be abandoned.

- The total salinity (or Total Dissolved Solids, TDS) in the groundwater at repository level must be less than 100 g/l. Higher values are acceptable in isolated areas that can be avoided and from which water will not flow to the repository area.

Of the above requirements, the concerns about the presence of valuable minerals and ore, the structural geology of the site, and the positioning of the repository within the rock mass to ensure adequate offset distance from major geological structural features are common to sedimentary and crystalline rock, although the structural geology may differ significantly (i.e., the presence and nature of regional plastic shear zones is uncertain in sedimentary rock). The requirement for excavation stability is also consistent with expectations for a DGR in sedimentary rock, although core discing is not necessarily a reliable indicator of potential excavation instability. The geochemical constraints at a particular site in sedimentary rock in Canada would likely differ from those proposed for crystalline rock in Sweden, and would probably depend in part on the selected conceptual design of the DGR and composition of materials used in the design.

In addition to the above requirements, Andersson et al. (2000) propose a large number of preferences (i.e., conditions that are desirable and should be taken into account when positioning the repository in the rock). Those preferences related specifically to the character or conditions of the rock mass are as follows:

- The deep repository should be sited in a commonly occurring rock type as it can be difficult to predict how different rocks and minerals will be used in the future.

- The density (fracture surface area per volume) of local minor fracture zones and fractures should not exceed moderate density.
- Initial rock stresses at the planned repository depth should not deviate from what is normal in Swedish crystalline bedrock.
- Strength and deformation properties of the intact rock should be normal for Swedish bedrock, as there has been positive experience with rock works in such bedrock.
- The coefficient of thermal expansion should have normal values for Swedish bedrock (i.e., within the range 10^{-6} to 10^{-5} K^{-1}) and should not differ markedly between the rock types in the repository area.
- The rock should have a thermal conductivity value greater than 2.5 W/(m K).
- The undisturbed temperature at repository depth should be less than 25°C. Areas with a high potential for geothermal energy extraction should be avoided.
- A large part of the rock mass in the deposition zone should have a hydraulic conductivity (K) that is less than 10^{-8} m/s. High permeability of the rock requires local adaptation of the repository if the safety margins are to be met.
- Fracture zones intersected during construction should have transmissivity (T) less than 10^{-5} m^2/s, and should not pose a constructability concern.

While the specific values suggested may or may not be suitable for other DGR concepts in sedimentary rock in Canada, the list identifies specific rock engineering parameters of importance in assessing the safety of a particular concept. Other preferences proposed by Andersson et al. (2000) related to hydrogeology and geochemistry are as follows:

- The local hydraulic gradient should be 1% or less at the repository level.
- Undisturbed groundwater at repository level should have a pH in the range of 6 to 10, a low concentration of organic compounds ([DOC] < 20 mg/l), low colloid concentration (lower than 0.5 mg/l), low ammonium concentrations, some content of calcium and magnesium ($[Ca^{2+}]+[Mg^{2+}] > 4$ mg/l) and low concentrations of radon and radium.
- A large portion of the rock with canister positions should have a Darcy velocity less than 0.01 m/year on a canister borehole scale, as lower flux increases retardation of important radionuclides.
- Substantial retardation of important radionuclides should take place in the geosphere. Quantitatively, Darcy velocity, flow distribution and the flow-wetted surface area per volume of rock (or equivalent parameter) should be such that the transport resistance (F parameter) for most flow paths is greater than 104 years/m.
- The matrix diffusivity and matrix porosity should not be much lower (by a factor of 100 or more) than the value ranges analyzed in the safety assessment SR 97 (SKB, 1999). The accessible diffusion depth should exceed at least a centimetre or so.

These factors are again related to the Swedish KBS-3 concept in crystalline rock and would require evaluation as part of a safety assessment of a particular design concept in sedimentary rock. As these factors are not specifically related to rock engineering, they are not considered further in this report.

The activities envisioned to enhance understanding of rock engineering-related conditions and characteristics of the subsurface host rock environment are as follows:

- Delineate major stratigraphic units and their spatial variability based on corelogging, downhole geophysical logging, and cross correlation with results from geophysical surveys and surface mapping.
- Delineate major structural geology features (e.g., faults) based on corelogging, downhole geophysical logging, and cross correlation with results from geophysical surveys and surface mapping.
- Identify and characterize discontinuity sets in each stratigraphic unit, including information on orientation, persistence, infilling, alteration, shape, and fracture surface roughness characteristics for use in rock mass classification.
- Determine representative rock properties (mechanical, thermal, chemical and hydraulic) based on laboratory testing of recovered core, and downhole geophysical logging. Specific properties are discussed in Section 5.
- Conduct in situ stress measurements in available boreholes to assess the magnitude, orientation and variability of the principal stress components with depth. Stresses in sedimentary rock may vary from one stratum to the next depending on tectonic and glacial loading history. Possible stress measurement techniques are discussed in Section 5.
- Conduct measurements of pore pressure with depth to establish a pore pressure profile in the various stratigraphic units. Pore pressure may vary in a stepwise fashion across different sedimentary strata depending on loading history, groundwater flow patterns, hydraulic properties, and other factors. Hydrogeological testing and sampling is also an important step to determine possible inflow and mass transport characteristics of the rock mass, and chemistry of the groundwater.
- Classify the rock mass in terms of geotechnical conditions that may affect development and operation of a DGR by applying standard rock mass classification systems (Geological Strength Index, Rock Mass Rating, Tunnel Quality Q) (Barton et al. 1974) using information from recovered core, geophysics, and borehole logs.

The staging of these activities may involve several scales of investigation, including the installation of regional boreholes in advance of selecting areas for more detailed investigation.

4.1.3 Data Management and Analysis

The development of a geosphere model of each site investigated is a vital step in organizing and consolidating technical information into a functional framework for analysis and presentation. The model requires a central database to manage collected data, and associated procedures for producing data plots and other output. Related actions include the following:

- Develop central database and data management system, and associated routines and procedures.
- Develop a preliminary geosphere model of the site, and compare conditions to site selection and exclusion criteria, based on the collected information. This step is intended as a high level screening to identify possible candidate sites.

- Conduct conceptual geomechanical analyses of typical excavated openings based on the collected data to identify potential design issues, and information needs for future underground characterization activities.

Analysis is discussed further in Section 4.2.

4.1.4 Summary - Rock Engineering in Technical Characterization

The main roles of rock engineering in technical siting of a DGR in sedimentary rock is to characterize the surface and subsurface rock mass in terms of the distribution of major geological features and lithostratigraphic units; determine the characteristics, properties and conditions of the rock mass that affect its response to DGR development; use the information to conduct engineering scoping analyses of DGR design concepts; and compare the collected information and analysis results. The primary rock mechanics requirements to complete these steps are as follows:

- Geological framework – develop a clear understanding of the surficial geology, lithostratigraphy, and structural geology of potential candidate sites. This requires compilation of information into a database from which to develop 3D models of surface and subsurface geological conditions, specifically a digital elevation model showing surface features, a lithostratigraphic model showing distribution of rock types, and a structural geology model showing distribution of faults/fracture zones.
- Rock properties – conduct laboratory and in situ testing to develop a database of rock mechanical, thermal, hydraulic and chemical properties for each of the major lithostratigraphic layers for use in site screening and selection. Identify possible ore or mineral horizons that may exclude the site from further consideration.
- Fracture and discontinuity characteristics – determine the characteristics and properties of fractures and discontinuities in each of the lithostratigraphic units, and of the major fracture zones and faults identified during site investigation. This includes hydraulic, thermal, mechanical and chemical characteristics and properties.
- In situ conditions – determine profiles of in situ stress, pore pressure, and temperature with depth for use in scoping analyses. Groundwater chemistry (particularly salinity) should be measured to ensure proper groundwater density is used in analysis, and to compare to exclusion criteria. Determine the seismic/tectonic history of each site and expected seismic conditions and associated parameters for dynamic analysis.
- Rock mass classification – classify the rock mass conditions using standard rock mass classification systems to assess tunnelling quality and possible support requirements to maintain stability of underground openings.
- Climatic conditions – determine the climatic conditions for each site based on climate records and forecasting of possible climate change effects. Determine the glaciation history for each site and identify possible glaciation-related features such as reactivated faults, isostatic rebound, and erosion potential.
- Engineering scoping analysis – conduct scoping analyses using simplified models to determine feasibility of constructing a DGR at each potential candidate site. The results from these analyses are intended to provide part of the basis for site

selection or exclusion. Engineering assessments are updated as new information is collected through subsequent activities, such as development of the UCF (see Section 4.2.2).

Rock engineering plays an important role in understanding the surface and subsurface conditions that may affect site selection for a DGR. Another important role of rock engineering at this stage is conveying technical results to the public through interactive meetings, conferences and discussions.

4.2 DESIGN

The engineering design process can be broken into three stages: conceptual, preliminary and detailed engineering. The successive design stages require increasingly accurate information related to in situ conditions and properties. Consequently, ongoing site characterization is an integral element of the design process to build on the information gathered during the site selection and investigation process. Much of this characterization work is conducted as part of the UCF development and operation, or is undertaken during construction. Figure 10 shows the Mol Underground Research Facility in Belgium, an example of a UCF where in situ tests in sedimentary rock (Boom clay) have been conducted. The selection (or development), testing and qualification of monitoring instrumentation and approaches, and their application to acquire baseline data and measurements during excavation and testing activities, is a second element of the design process. In conjunction with ongoing site characterization and monitoring, the selection (or development), testing and qualification of analytical tools and approaches is a third element of the design process. These analytical tools/approaches derive their inputs from the collected site characterization and monitoring data.

Figure 10: Mol Underground Research Facility in Boom Clay, Belgium (R. Read)

The role of rock engineering in the design process includes aspects of each of these three elements. Characterization of the rock mass requires geological and geotechnical observations of in situ conditions based on borehole and geophysical data, prediction of conditions expected during excavation, and confirmation of conditions following excavation. This cycle of observation-prediction-confirmation is vital to develop confidence in the geosphere model, the rock mass classification, and the adopted characterization methodology. Monitoring of the rock mass is intended to quantify the rock mass response to excavation, the effects of changes in environmental conditions (e.g., temperature and humidity), and the interaction of the rock mass with engineered components (i.e., critical interfaces in the DGR design). Numerical models and analytical tools capable of reproducing and predicting the observed conditions and measured responses are the critical link between characterization, monitoring, and detailed design. Depending on the observed rock mass conditions and responses, significant development work may be required to either adapt available numerical and analytical tools to function in a predictive capacity, or create new tools and techniques. The outputs from the design process are increasingly detailed designs for the DGR and its associated components, and a detailed construction plan for its development.

4.2.1 Design Stages

The three engineering design stages associated with a DGR are described as follows:

- Conceptual engineering design of the DGR involves using available or estimated values for key rock properties and in situ conditions to asses the feasibility of alternate repository layouts to meet design specifications. These types of studies have been conducted to support AECL's EIS (AECL, 1994) and more recently the NWMO's recommendation on Adaptive Phased Management (Read, 2008). Conceptual design is intended to be adaptable to different site conditions, and therefore does not rely on site-specific information to a large extent.

- Preliminary engineering design is conducted once potential candidate sites are identified. At each of the candidate sites, information collected during the site investigation phase is fed into the design process to test the conceptual design under specific conditions expected at the site. Given the preliminary nature of the information collected prior to development of a UCF at the preferred candidate site, there is a relatively high level of uncertainty associated with the preliminary design. Nonetheless, using sensitivity analyses based on conservative assumptions where data are lacking, it is possible to identify engineering refinements required to meet the design specifications, or severe issues that may limit or preclude construction of the DGR at a particular site.

- Detailed engineering design is undertaken once a preferred candidate site is identified, and a UCF is constructed to gather site-specific information and to conduct experiments and component demonstrations. This stage of the engineering design process reduces the uncertainty inherent in the preliminary design by considering site-specific information collected in situ. Information from research activities and component demonstrations is also used to refine specific aspects of the design. This refinement may be staged to allow construction of facilities and underground openings to proceed, followed later by detailed design of sealing systems, for example. The detailed design must meet design specifications, and will therefore involve monitoring to demonstrate compliance.

While engineering design is in many respects a parallel process to site characterization and construction, and the transition from preliminary to detailed engineering design is progressive, it is fair to say that detailed engineering design starts with UCF construction and evolves throughout DGR construction into extended monitoring. Certain aspects of the DGR design will be finalized early in the process (e.g., the dimensions and locations of access and ventilation shafts), while others will require long-term monitoring to confirm design details (e.g., sealing systems). To provide a context for rock engineering issues associated with engineering design, the development of the UCF is described below, followed by a discussion of rock engineering issues associated with engineering design.

4.2.2 Underground Characterization

Once a siting decision is taken and a preferred candidate site is selected, further underground characterization is necessary to confirm rock mass characteristics, properties and in situ conditions. The construction of the UCF involves excavating underground openings to conduct in situ characterization activities, experiments and technology demonstrations. Rock engineering-related activities for UCF development are as follows:

- Using the preliminary geosphere model of the site based on borehole and geophysical data, predict geological/geotechnical conditions expected during UCF excavation. Confirm conditions following excavation by comparing predictions and observations, and update the geosphere model, the rock mass classification, and the adopted characterization methodology accordingly. Back analysis of actual conditions is expected to improve predictive models.

- Instrument the rock mass prior to UCF shaft excavation and conduct mine-by type rock mass response experiments through instrumented arrays to back analyze rock mass properties. In sedimentary rock, locations of instrumented arrays should be selected strategically to target strata of particular relevance to long-term isolation of nuclear fuel waste. Install long-term monitoring instruments in subsurface boreholes to provide baseline data on rock temperature and pore pressure.

- Demonstrate excavation and ground support technologies, and assess construction productivity during shaft excavation to access experimental levels. This is a construction activity but is listed here for completeness.

- Map geological/geotechnical conditions in all excavations using standard mapping techniques on a photomosaic base. This can be facilitated with the use of 3D photoscanners to develop a 3D base map. Laser scanners can be employed to determine excavation geometry. These automated techniques are of particular value in situations where the excavation cannot be left unsupported for any length of time due to rapid rock mass deterioration resulting from wetting or desiccation (i.e., slaking behaviour). This type of behaviour is common in some sedimentary rocks (e.g., shales, siltstones and claystones).

- Conduct underground geophysical surveys and borehole drilling to characterize the rock mass at repository depth, and in the vicinity of excavated shafts. Corelogging and sampling for laboratory testing is required to update the geosphere model, the rock mass classification, and rock properties database. The possibility of sample damage in core should be considered in selecting samples for testing. Particular emphasis is placed on identifying major faults and fracture zones for obtaining rock and groundwater samples, and for in situ testing (e.g., hydraulic testing to determine hydraulic properties).

- Conduct in situ testing at specific locations to measure in situ mechanical and hydraulic properties of the rock mass, and to determine the extent of excavation-induced damage. Mechanical properties can be deduced from geophysical measurements, plate-loading or flat-jack tests, or borehole jacking tests, depending on the type of rock and its properties. Hydraulic packer tests in boreholes provide the basis for estimating hydraulic properties. Excavation damage can be identified using a combination of geophysical techniques, such as seismic reflection, seismic refraction, crosshole velocity surveys, and acoustic emission/microseismic monitoring. Calibration of these techniques in different sedimentary rock strata is required as part of the in situ characterization of the rock mass.

- Conduct in situ stress measurements using a variety of techniques to develop a detailed understanding of stress conditions with depth. Such techniques could include overcoring, under-excavation, hydraulic fracturing, and back analysis of mine-by monitoring results (Read, 1994). Conditions in some sedimentary rocks may limit the types of measurements possible (e.g., effects of rock anisotropy, difficulty in gluing on strain gauges, etc.). Stress conditions may vary considerably from one stratigraphic unit to the next, so many measurements are required to fully characterize the in situ stress conditions.

- Conduct pore pressure measurements in each stratigraphic unit to assess pore pressure distribution with depth. Different types of piezometers are available for these types of measurements. Some fine-grained sedimentary rocks may take a long time to equilibrate and therefore instrument sensitivity and long-term reliability are considerations in instrument selection.

- Design and conduct in situ demonstration tests of single and multiple engineering design components under ambient and elevated temperature conditions to validate/calibrate numerical models and confirm engineering performance. For each of these tests, rock mass monitoring is used to measure the rock mass response to excavation, the effects of changes in environmental conditions (e.g., temperature and humidity), and the interaction of the rock mass with engineered components (i.e., critical interfaces in the DGR design). Refinement of numerical modeling tools should be anticipated.

- Conduct uncoupled and coupled thermal-mechanical-hydraulic (TMH) analyses of the DGR design excavations and arrangement based on the updated geosphere model and associated characterization and monitoring data. These analyses are intended to identify potential design issues, and to help refine the DGR design to meet design specifications.

- Produce an updated DGR design and construction execution plan based on the results from the siting and UCF investigations.

In order to proceed with detailed engineering design, several aspects related to the rock mass must be understood:

- Potential failure modes around excavations at the DGR level and shafts to select appropriate analysis methods and tools.

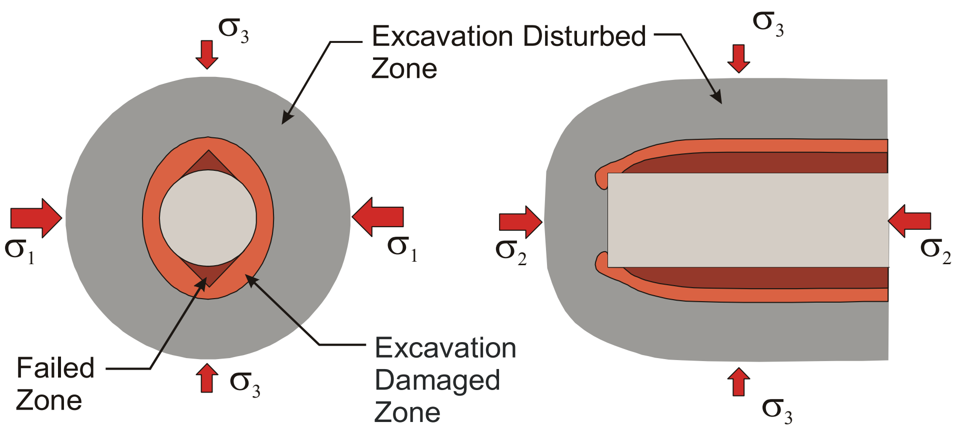

Figure 11: Disturbed, Damaged and Failed Zones Around an Excavation (Read, 2004)

- Rock mass strength characteristics and their relation to stress path to develop representative strength envelopes for analysis of damage development and progressive failure.
- Rock mass mechanical and thermal properties, and thermal expansion coefficients, to account for deformation and possible shearing along interfaces between different strata. This includes characteristics of the excavation damaged zone (EDZ) around underground openings (Figure 11).
- In situ stress, pore pressure and temperature conditions with depth, and estimated variations under thermal and glacial loading, to impose realistic boundary conditions in design analysis.

Martin et al. (2001) emphasize the need to understand the possible failure modes around underground openings in hard rocks, and their relation to the stress path experienced by the rock mass. Structurally-controlled failure may dominate in situations where stress relaxation occurs around underground openings, allowing movement of rock wedges or blocks in fractured rock. In highly stressed environments, underground openings may experience spalling and progressive failure. The combined effects of mechanical loading due to excavation, thermal loading due to waste placement, and glacial loading must be taken into account in the design process. In addition, the spacing and sequencing of adjacent underground openings may affect the near-field stress conditions, and may lead to failure by one of these modes (i.e., over-stressing or relaxation). The strength envelopes to be used for design analyses must also account for stress path effects, scale effects, and possible sample damage effects in recovered core samples. Considerable work has been published on strength envelopes for excavation damage and stability analysis (e.g., Read et al.,1998; Martin et al., 2001; and Diederichs, 2007). This work can be adapted to sedimentary rock environments through carefully planned laboratory and in situ testing of relevant rock types.

Rock mechanical and thermal properties, as well as thermal-mechanical and thermoporoelastic coupling parameters, can be determined through a combination of laboratory and in situ testing. Read and Chandler (2002) describe standard and specialized laboratory testing conducted on granite for the Thermal Mechanical Stability Studies. Standard rock mechanical tests include unconfined and triaxial compression tests, direct and Brazilian tensile tests, and elevated temperature tests. Modified procedures were developed for damage-controlled testing to examine post-failure behaviour of the rock (Lau et al., 1996; Lau and Chandler, 2004). These tests involved servo-controlled cyclic loading of samples to track the evolution of properties including strength, Young's modulus, and Poisson's ratio as crack damage accumulated in the samples. The analysis of these tests focused on defining the characteristics of the rock associated with the stress at the onset of dilation, or volumetric strain reversal (Martin and Chandler, 1994). This point on the stress-strain curve was termed the crack damage stress (σ_{cd}), and was taken as an indication of long-term rock strength.

In addition to these tests, Lau and Chandler (2004) describe long-term loading tests conducted under various confining stresses at ambient and elevated temperature on water-saturated samples of rock. These tests were designed to investigate the relation between crack damage stress and long-term rock strength, the time-to-failure response for rock, and the effect of temperature on creep behaviour. The stress-strain results from these tests were used to calibrate numerical models of stress corrosion (Potyondy and Cundall, 2004). Finally, new laboratory tests developed to determine the thermoporoelastic properties of rock were conducted in parallel with the in situ Thermal Hydraulic Experiment at AECL's URL (Lau and Chandler, 2004). These tests were shown to successfully estimate the thermoporoelastic coupling parameters required to predict thermally-induced pore pressure in situ (Detournay and Berchenko, 2001; Berchenko et al., 2004; Detournay et al., 2004).

The suite of laboratory and in situ tests conducted to determine relevant properties of granite can be used on samples of other rock types. For sedimentary rock, additional testing procedures or modifications to existing procedures may be required to account for anisotropy in some cases (e.g., shales). As well, slake durability testing is required to assess the likelihood of rapid rock deterioration under wetting and drying cycles. Some marine shales have been shown to be sensitive to contact with fresh water, and may exhibit swelling behaviour. For example, samples of the Queenston Shale of the Michigan Basin swell in fresh water (Lo, 1989). Oedometer and creep testing may be appropriate if these types of rock are present at the DGR level or in the shafts. Other testing designed for oil field shales to assess capillary pressure and relative permeabilities to gas and water are also be applicable to address gas generation and migration issues. The results from these types of tests should be taken into account in specifying strength envelopes for design analysis.

In situ characterization of the near-field excavation damage zone (EDZ) around underground openings is another important aspect of underground characterization (Martino and Chandler, 2004). As explained by Read and Chandler (2002), measuring excavation damage and monitoring the processes associated with its development provide qualitative and quantitative information on in situ conditions and changes in rock properties near underground excavations. In the context of repository excavation design, this type of information from prototype excavations can be used to predict excavation response expected during construction and operation of a repository. Ongoing measurements during construction can be used to calibrate numerical models, and to identify unusual conditions associated with variability in geology or other in situ conditions.

The EDZ characteristics that are of interest for repository excavation design are: 1) geometry of the damaged zone including shape and depth into the rock mass; 2) mechanical properties including elastic deformation moduli, Poisson's ratio, ultrasonic velocity, dilation angle, and strength envelope; 3) hydrogeological properties including porosity, permeability, transmissivity, and Biot's coefficient; and 4) thermal properties including thermal conductivity and thermal expansion coefficient. By quantifying changes in moduli and acoustic velocity, inferences can be made regarding the degree of cracking in the rock, and hydraulic properties of the damaged rock (Read and Chandler, 2002). Martino (2000) summarizes EDZ characterization techniques applicable to granite. Table 1 presents the techniques used for comprehensive characterization of the Tunnel Sealing Experiment test tunnel (Read and Chandler, 2002). These techniques can be adapted to sedimentary rock conditions.

Comprehensive in situ stress measurement programs have been undertaken at the URL in Canada and the Aspö Hard Rock Laboratory (HRL) in Sweden. The different stress measurement methods employed at the URL, and their results, have been well documented (Chandler et al., 1996; Martino et al, 1997; Thompson et al., 2002). Thompson and Chandler (2004) describe the use of hydraulic fracturing and the Deep Doorstopper Gauge System at the URL for measurement of stresses to 1000 m depth. Martin et al. (2001) summarize the stress characterization programs in Canada and Sweden. Some of the important findings to consider for such a program in sedimentary rock are as follows:

- The various stress measurement techniques have limitations in their applicability to certain rock conditions. For example, overcoring does not produce reliable results if core discing is evident because the rock does not behave in a linear elastic manner. Likewise, gluing strain gauges to some rocks is difficult or impossible if they soften in the presence of water (e.g., weak shales and claystones). These limitations must be considered in planning a stress measurement campaign.

- Tectonics and geological structures such as faults and fracture zones are likely to affect the in situ stress magnitudes and orientations, and introduce possible variability in the stress conditions. Likewise, fracturing in the rock mass may disrupt the in situ stress field and result in localized stress perturbations. Large-scale back analysis techniques may overcome some of this variability. In general, multiple measurement techniques, and redundant measurements are required to provide confidence in the stress measurements.

In sedimentary rock, anisotropy in rock fabric may affect the interpretation of stress measurements as determined from overcoring, under-excavation or hydraulic fracturing. However, correction for anisotropy has been successfully applied to overcoring stress determinations at the URL in Canada to develop a consistent interpretation of in situ stresses (Martin and Christiansson, 1991; 1991b). Indicators such as borehole breakouts and core discing may also help quantify stress orientations and, in some case, may help to constrain the limits for in situ stress magnitudes and/or horizontal stress ratios. These indicators may also be influenced by anisotropy in the rock mass. Laboratory testing to determine the degree of anistropy in the principal rock types intersected by underground openings should therefore be undertaken in parallel with stress measurements.

4.2.3 Engineering Design Analysis

According to Read and Chandler (2002), the primary DGR design issues related to rock engineering are:

- Excavation stability - instability of underground openings in the short-term can affect safety during construction and waste placement/sealing operations; in the long-term, it can affect the load transferred to containers and seals, and can affect the performance (and predictability of performance) of repository sealing systems.

Table 1: EDZ Characterization and Monitoring Techniques (Read and Chandler, 2002)

Tool or Technique	Type	Measured Quantity	Application	Comments
Mini-CHARTS crosshole seismic survey (AECL)	Geophysical	P- and S-wave transit time between boreholes.	Tomographic imaging in panels between boreholes; detection of lithologic changes and fracturing. Two borehole arrays with four panels used in TSX tunnel.	Frequency range 1 to 5 kHz over distances of 20 to 500 m; 3 to 40 kHz over distances of 0.5 to 60 m. Requires accurate borehole surveys.
Seismic refraction survey (Applied Seismology Consultants)	Geophysical	P-, S- and refracted wave transit times in tunnel wall.	Detection of refracted waves to identify interface between damaged and intact rock (contrast in acoustic impedance). Used to estimate depth of damage. Seven horizontal survey lines used in TSX tunnel.	15 accelerometers with frequency range 1 Hz to 10 kHz transducers coupled to rock in blasthole half-barrel remnants. Pulse provided by Schmidt hammer.
Microvelocity surveys (Applied Seismology Consultants)	Geophysical	Ultrasonic interval velocity along a borehole	Detection of velocity variations resulting from excavation damage near tunnel. Measurements taken every 5 cm in first metre and every 10 cm in remainder of 16 boreholes (two arrays) in TSX tunnel.	Travel time between transducers of fixed spacing. Spacing determines depth of penetration away from the borehole. Damage profile along boreholes radial to the tunnel.
SEPPI probe surveys (ANDRA)	Hydraulic	Pressure-pulse decay	Direct measure of interval permeability in boreholes at different radial distances from tunnel. Sensitive to condition of the borehole wall.	Probe uses two hydraulic and two mechanical packers. Requires rock to be saturated with water. Syringe-type pump injects water at high pressure, injected volume measured to 0.1 mm^3.
Connected permeability test (AECL)	Hydraulic	Hydraulic conductivity	Direct measure of connected permeability of the floor of a tunnel. Measure seepage rate under a known head of water through a known cross-sectional area of flow. Full-scale flow characteristics.	Dam and reservoir used to create constant head conditions. Flow into a drilled slot measured with time. Bentonite strips used in TSX to seal concrete-rock interface.
Corelogging (AECL)	Geological	Lithology and fractures	Direct observation of geological variability, discing and induced fracturing in core. All TSX instrument and characterization holes logged.	Discing-type damage in core is unrelated to damage in situ. Velocity of core typically half that of in situ rock mass indicating core damage. Useful for interpreting geophysical results and identifying natural fractures.
Geological mapping (AECL)	Geological	Lithology and fractures	Direct observation of geological variability, natural and induced fractures in excavations. All TSX access tunnels and main test chamber mapped.	Useful for interpreting other characterization results. Geological variability affects mechanical response. Maps and photo mosaics used for detailed mapping.

Table 1 (continued)

Tool or Technique	Type	Measured Quantity	Application	Comments
Borehole camera surveys (AECL)	Geological	Lithology and fractures	Direct observation of geological variability, natural and induced fractures, and breakouts in boreholes. All 16 MVP boreholes surveyed in TSX tunnel.	Microcracks, borehole breakouts and blast-induced fractures observed in boreholes. Breakouts indicate high compressive stresses and are problematic for SEPPI measurements.
Microseismic monitoring system (Applied Seismology Consultants)	Geophysical	Induced microseismicity	Microseismic source location and mechanism analysis. Identifies where microcracking is occurring around the TSX tunnel.	Continuous monitoring of induced microseismicity prior to, during and after excavation of the TSX tunnel, and during operation of the experiment. Synchronized with AE system. Frequency range 0.1 to 50 kHz.
Acoustic emission monitoring system (Applied Seismology Consultants)	Geophysical	Induced acoustic emissions	Acoustic emission source location and event mechanism analysis; repeated velocity surveys.	Continuous monitoring of induced acoustic emissions in a small rock volume near the clay key. Frequency range 50 to 5000 kHz. Synchronized with MS system.
Hydrogeology packer system (AECL)	Hydraulic	Pore pressure	Pore pressure at different locations around the test tunnel. Installed prior to TSX tunnel excavation.	Measure pore pressure response associated with excavating the TSX tunnel. Compare to predicted response.
Excavation Damage Assessment (EDA) Packers (AECL)	Hydraulic	Pore pressure	Pore pressure and hydraulic interconnection in excavation damaged zone (EDZ) in rock within 1 m of TSX tunnel near seal locations	Small interval packer strings with four intervals, 100 to 400 mm in length separated by 25 mm hydraulic glands.
Extensometers (AECL)	Mechanical	Displacement	Deformation response of the rock mass to excavation of the TSX tunnel.	Measure displacement response associated with excavating the TSX tunnel. Compare to predicted response.

Note: Performing organizations shown in parentheses

- Excavation damage - the development of damage around underground openings can affect the mechanical and hydraulic/transport characteristics of the near-field rock mass, which may affect the long-term performance of tunnel and shaft seals.

Martin et al. (2001) suggest that the single most important rock mechanics objective for successful design of a DGR is for the underground openings to perform as intended. This normally implies that the underground openings must remain stable for their operating life, but does not necessarily preclude the occurrence of localized failure around excavations. However, the amount of failure must be minimal such that the openings remain functional. The authors define the modes of failure typically observed around underground openings, techniques available to assess failure potential, and mitigation options to control failure.

Read and Chandler (2002) concur that, in designing excavations associated with a DGR, a key objective is to maintain stable rock mass conditions around each underground opening throughout the DGR's life cycle. However, a second key objective is to minimize excavation damage that can adversely affect the hydraulic performance of the repository. During the extended time period over which a DGR is expected to contain and isolate nuclear fuel waste (up to 100,000 years), the rock mass will be subjected to mechanical loads generated by stress redistribution around underground excavations, support loads introduced by buffer and backfill materials, and thermal loads generated by the placed nuclear fuel waste. Other load changes, such as those associated with glaciation or erosion, are also possible over the long term. To design stable openings with minimal damage, numerical models and/or other analytical tools are required to assess the effects of these anticipated changes in boundary and initial conditions on the rock mass response. Excavation stability is dependent on a number of factors including rock mass properties, fracture characteristics, in situ stresses, pore pressure, excavation method, excavation geometry and orientation, and construction sequencing (Read, 2003). These factors must each be considered as part of DGR excavation design.

In early stages of design, empirical methods based on rock mass classification (e.g., the Tunnelling Quality Index Q) or simple closed-form solutions based on linear elasticity are generally sufficient for assessing the stability and possible ground support requirements for a single opening. For excavation shapes without quarter-symmetry (i.e., U-shaped openings), and multiple parallel openings, 2D numerical modeling codes (e.g., FLAC[3], PHASE2[4], EXAMINE2D) have been used successfully in sparsely fractured rock environments to predict the onset of brittle failure. To account for 3D effects near the advancing tunnel face, codes such as EXAMINE3D and FLAC3D can be utilized to identify where the strength to stress ratio reaches unity around the opening(s). In fractured rock, alternative discrete element codes such as UDEC and 3DEC have been used to simulate fracture networks. These networks can be generated on a probabilistic basis using tools such as FRACMAN[5], incorporating collected information on fracturing from characterization activities. For blocky rock conditions where wedge failures control tunnel stability, key block analysis codes are more applicable.

Each of these numerical tools has limitations with respect to predicting the extent and characteristics of excavation damage, and the extent to which progressive failure will advance into the rock mass. Where the rock mass can be considered a continuum, Martin et al. (2001) propose the use of FLAC with a customized subroutine to account for the loss of cohesion prior to mobilization of friction. This subroutine essentially simulates a compound failure envelope, with the initial analysis conducted assuming a Hoek-Brown m-value of zero (corresponding to a friction angle of zero). Diederichs (2007) demonstrates this approach by back analyzing the observed depth and shape of the progressive failure zone around the URL Mine-by Experiment test tunnel. While this approach does not simulate the discontinuum nature of the failure process, and requires specialized laboratory testing to calibrate the subroutine parameters, it

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[3] FLAC (Fast Lagrangian Analysis of Continua), FLAC3D, UDEC (Universal Distinct Element Code), and 3DEC – commercial software from HCItasca, 111 Third Avenue South, Suite 450, Minneapolis, MN 55401, USA

[4] PHASE2, EXAMINE2D and EXAMINE3D – commercial software from Rocscience Inc., 31 Balsam Avenue, Toronto, Ontario, M4E 3B5

[5] FRACMAN – commercial software from FracMan Technology Group, Golder Associates Inc., 18300 NE Union Hill Road, Redmond, WA 98052 USA

does represent one approach to assess the potential depth and geometry of the failed zone in homogeneous sparsely fractured rock. For anisotropic sedimentary rock, or fractured rock conditions, an alternate or modified approach may be required.

As part of the Thermal Mechanical Stability Studies at the URL (Read and Chandler, 2002), considerable effort was spent developing a numerical modeling tool capable of capturing the transition from continuum to discontinuum behaviour, tracking the development of excavation damage, and predicting the extent and shape of the progressive failure zone. Potyondy and Cundall (2004) describe a bonded-particle model (BPM) of rock based on the distinct element codes PFC2D and PFC3D. The models require specification of stiffness and strength micro-properties for particles and bonds. Damage is represented explicitly as broken bonds, which form and coalesce into macroscopic fractures when load is applied. The model was shown to reproduce many observed features of rock behaviour including elasticity, fracturing, acoustic emission, damage accumulation producing material anisotropy, hysteresis, dilation, post-peak softening, and strength increase with confinement. These behaviours are emergent properties of the model that arise from a relatively simple set of micro-properties. Particle size in the model was shown to be linked to fracture toughness. Although promising as a predictive tool for both excavation damage and progressive failure, the calibration of the model and derivation of appropriate micro-properties is a relatively intensive process. Read and Chandler (2002) also outlined some of the deficiencies in the modeling approach that could likely be overcome with further research and development. Issues of anisotropy and fracturing in sedimentary rock may pose additional challenges to the application of this type of model.

Mitaim and Detournay (2004) developed a micro-mechanical damage model as part of the Thermal Mechanical Stability Studies to predict the development of damage in granite. This approach is based on a sliding/wing crack model and can be implemented in a continuum numerical code such as FLAC. Simple demonstration cases simulated with the model showed that it was able to reproduce the complex stress-strain behaviour obtained in laboratory experiments. Further development of a fully-functional numerical code was not completed as part of the Thermal Mechanical Stability Studies, but the model can be adapted as a subroutine within a continuum code such as FLAC.

In terms of design analysis for a DGR in sedimentary rock, the numerical tools described above each offer some advantage. The specific conditions of the rock mass will dictate to a large extent the most appropriate analysis method. Additional development of numerical tools, if required, should be considered as early as possible in the DGR development process to allow adequate time for testing and calibration of any new or refined numerical tool. Where possible, multiple analysis tools should be employed to provide confirmation of predictions.

Martin et al. (2001) also consider pillar stability and rock bursting potential in the design process. Both of these rock engineering aspects are linked to possible rock mass instability. Martin et al. (2001) propose an approach to pillar stability analysis incorporating the notion of cohesion loss preceding mobilization of friction rather than relying on empirical pillar stability design approaches. While the authors found good agreement between predicted and observed conditions for relatively thin pillars, no calibration data were available for relatively wide pillars (width/height ratios of 1.5 or greater). Further work on pillar stability was conducted at the Aspö HRL, focusing on the pillar between adjacent deposition boreholes in the KBS-3 concept (e.g., Andersson, 2007). The results of this in situ experiment were not reviewed as part of this report, but further study is required in this topic area in relation to sedimentary rock. It is possible that higher ductility of some sedimentary rocks such as shales may reduce the potential for rock bursting. A literature review of mining experience in sedimentary rock is considered a logical first step.

Rock bursting potential for typical low extraction ratios associated with a DGR in crystalline rock was considered minimal by Martin and Chandler (1996) and Martin et al. (2001). Current mining guidelines are considered applicable for a DGR in crystalline rock, and are likely adaptable to a DGR in sedimentary rock. Fault identification and characterization is required to assess the potential for a fault-slip type rock burst. Read (2008) conducted a scoping analysis of the potential for large-scale fracturing associated with a DGR in crystalline or sedimentary rock, and found that in the absence of large-scale erosion, or high thermally-generated pore pressures, large-scale rock fracturing was unlikely to occur over the lifetime of a DGR.

4.2.4 Summary - Rock Engineering in Design

The role of rock engineering in these various design stages involves several activities:

- Characterization - Plan and conduct controlled laboratory and in situ tests, experiments, and demonstrations to determine or confirm specific aspects of material and component behaviour and/or performance, and to provide data for model calibration/validation. The development of damage in the near-field rock mass is a specific rock mechanics issue requiring investigation. Single- and multi-component tests, experiments and demonstrations are required to ensure material behaviour and interactions between system components are understood.

- Monitoring - Select and deploy instrumentation to monitor component and system performance during construction and for tests, experiments and demonstrations in the UCF environment. Longevity and reliability of instrumentation are two important design considerations.

- Analysis - Develop criteria and correlations, and associated application methodologies, that bridge the gap between laboratory and in situ data, particularly with respect to long-term rock strength and scale effects. This aspect of rock engineering is particularly challenging. Recent work by Diederichs (2007) has advanced the findings of the Thermal-Mechanical Stability Studies (Read and Chandler, 2002) for crystalline rock. A similar line of reasoning is required to ensure material behaviour of sedimentary rock is treated consistently at both the laboratory and field scale in numerical models.

- Numerical modeling - Select (or develop), test and qualify design tools such as numerical modeling codes and analytical methods, using results from controlled laboratory and in situ experiments and tests to validate the tools. Qualification of design tools is essential to build confidence in their application to DGR design.

- Excavation design - Refine the repository layout and excavation designs to meet design specifications, using detailed site characterization data obtained from in situ characterization activities and monitoring. This would involve room and pillar dimensioning to ensure long-term stability of the repository, as well as excavation sequencing and selection of suitable excavation methods and equipment.

- Ground support design - Design and implement ground support systems as required to maintain stability of underground openings for the duration of the construction stage, and beyond into the long-term monitoring stage. This activity carries into construction.

- Sealing system design - Design sealing systems compatible with in situ rock mass conditions to ensure containment of radionuclides for the requisite containment period. Of particular interest are the interfaces between the clay- and concrete-based sealing components and the rock mass, including design of rock cutoff keys (Martin et al., 1996; Read and Dixon, 2003). This activity carries into construction.
- Performance verification - Verify overall system performance to support a decision to close the repository. This activity carries into post-construction.

4.3 CONSTRUCTION AND OPERATION

A DGR will comprise a series of underground openings including shafts, access tunnels, placement rooms, and other excavations required for underground operations. The excavations and near-field rock mass (i.e., the rock mass close to the openings) constitute a unique environment, with conditions distinct from the surrounding geosphere. Excavations will remain open during repository construction and operation, and will be sealed following placement of used fuel. Temporary ground support may be used in the short-term to provide a safe working environment; it may or may not be removed during backfilling/sealing.

4.3.1 Excavation Sequencing

According to NWMO (2005), the construction and operation stages of DGR development are sequential, implying that all excavation work may be completed prior to placing nuclear fuel waste in the DGR. This approach has the advantage of allowing complete characterization of all underground openings using the techniques described in Section 4.2.2 prior to used fuel placement, thus allowing adjustments to be made to the placement strategy to accommodate any unfavourable geological features identified. This approach also reduces the possible exposure of construction workers to radiation hazards, and eliminates the possible risks associated with blasting in the vicinity of placed nuclear fuel waste. The disadvantage of this approach is that the earliest excavations will remain open for a period of up to 10 years without the ameliorating effects of backfill to reduce deterioration of the rock due to environmental, stress relief and blasting effects. This is a particular concern in some sedimentary rock where slaking, swelling and rheologic behaviour of the rock mass may result in significant loss of integrity in the near-field zone.

An alternative approach mentioned briefly in NWMO (2005) is concurrent excavation and placement of nuclear fuel waste. In this approach, construction and operation of the DGR overlap as placement rooms are excavated in panels, used fuel is placed, and rooms are backfilled in sequence rather than excavating all placement rooms prior to placement. This approach reduces the risks associated with rock mass deterioration and provides the opportunity to monitor early placement rooms to ensure compliance with specifications. However, the transport and placement of used fuel in concert with ongoing construction activities involving blasting and material handling requires strict planning and implementation of safeguards to ensure radiation safety and avoid interference between the two activities. This approach also limits ongoing characterization and design refinement to individual panels of placement rooms, and may increase the risk of encountering a major unexpected geological feature (e.g., fault or fracture zone) until after initial placement of nuclear fuel waste. These competing advantages and disadvantages need to be considered in selecting the preferred path forward. Host rock type affects the decision on excavation sequencing.

4.3.2 Other Considerations

Regardless of excavation sequence, stress history associated with blasting and proximity of adjacent excavations must be taken into account in construction execution. Related construction issues include the selection of excavation method, estimating productivity and effects of tool-rock interaction on equipment wear, selection and installation of ground support systems, and remediation of intersected faults and fracture zones using grouting techniques. Ground support options are limited in some cases. For instance, some shales require immediate coverage with shotcrete or concrete lining to prevent desiccation and deterioration. As well, rock bolts may be of limited use in some rocks due to poor bonding or anchoring characteristics. Backfilling of placement rooms following placement of UFCs, and construction of concrete bulkheads at the entrance to filled rooms, are required to limit radiation exposure and to allow buffer and backfill materials to develop swelling pressure. The construction of bulkheads will likely involve grouting at the concrete rock interface to ensure proper sealing. Chemical interactions between the concrete, clay-based sealing materials and the rock mass are affected by host rock type.

The primary role of rock engineering during construction/operations is to conduct ongoing characterization of DGR excavations, update the geosphere model and rock mass classification, and adjust the DGR design and construction execution plan accordingly. Back analysis of observed behaviours and measured responses is an integral part of design refinement. Active involvement in the selection/design, implementation and monitoring of excavation methods, ground support, and sealing systems is also a priority. The design and implementation of appropriate monitoring systems, and ongoing management and analysis of monitoring data, is an important function at this stage of DGR development.

Excavation methods for DGR openings have been investigated at the URL and Äspö HRL. The various approaches for horizontal excavation have included drill-and-blast, tunnel boring and hydraulic rock splitting (Olsson et al., 1996; Read and Martin, 1996). Vertical shafts have been excavated using drill-and-blast, raise-boring, and blind boring (Read, 2004). In addition, drill-and-blast ramps have been developed to access different levels at both facilities. The Excavation Stability Study at the URL (Read and Chandler, 1997; Read et al., 1997; Read, 2003, 2004) demonstrated the flexibility inherent in the drill-and-blast method for creating openings of non-circular shape to accommodate the in situ stress field (Figure 12). This study demonstrated that tunnel geometry can be adjusted to create stable openings with minimal excavation damage in adverse stress conditions, but requires a high degree of confidence in the in situ stress conditions and rock mass properties at a particular site. The use of rectangular openings in the Canadian mining industry (Martin et al., 2001) may be effective in reducing crown stability issues, but may lead to continuous zones of damaged rock near the sharp corners of the openings (Read, 2004). Aside from excavation shape, other excavation considerations include the orientation and relative spacing of access tunnels and placement rooms.

Ground support design in crystalline rock has received relatively little attention owing to the generally competent nature of the rock mass around underground excavations at the various international research sites. Typically light rock-bolting and screening of the crown of excavations has been sufficient to prevent slabbing in highly stressed, sparsely-fractured rock conditions at the URL. More extensive bolting may be required in more fractured rock. Empirical approaches to select tunnel support based on rock mass classification are suitable for construction planning (Martin et al., 2001). Detailed support analyses can be conducted using structural elements in FLAC or other continuum codes. This latter approach may be better suited to layered sedimentary rocks. Alternate design tools may be required for fractured rock. The longevity of bolts under high saline conditions is another consideration in support design.

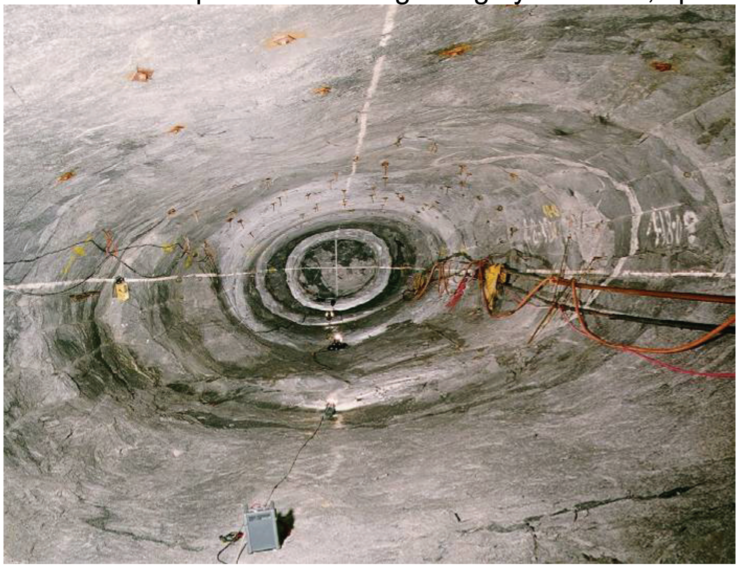


Figure 12: Stable Inclined Drill-and-Blast Tunnel from the Excavation Stability Study (Read and Chandler, 1997)

Considerable work has been conducted on tunnel sealing systems at the URL. The Tunnel Sealing Experiment (Chandler et al., 2002) provides a comprehensive study of clay- and concrete-based bulkheads in granite. The use of cut-off keys excavated into the rock mass at bulkhead locations was shown to be an important component of seal design (Martin et al., 1996). Additional work under the Engineering Design of Repository Sealing Systems (ENDRES) project at the URL was aimed at closing remaining knowledge gaps with respect to sealing systems and associated technology (e.g., Read and Dixon, 2003). The Prototype Repository at the Äspö HRL is a full-scale in situ experiment currently underway to study sealing system performance, among other things. Other international repository research programs (e.g., USDOE OCRWM, 2001) have also considered options for tunnel sealing and bulkhead design, including grouting and borehole sealing. These studies are a basis for additional studies in specific sedimentary rock types.

Grouting technology and approaches have also been investigated at the URL (e.g., Gray and Keil, 1989). In situ tests of grouting a major fracture zone demonstrated that specialized cement- and clay-based grouts can effectively seal water-bearing zones. The development of microfine cement grouts has been an area of active research at the URL. International studies of grouts and grouting have also been documented (Gray, 1993). . Assessment of the effectiveness of these types of grouts in sedimentary rock will require in situ trial testing, as well as chemical testing in the laboratory to assess the potential for undesirable interactions with specific rock types. Studies into the possible erosion of grouting materials are also envisioned.

Monitoring technologies have been advanced through the research programs at the URL in Canada and elsewhere. The various tools and techniques used in the Tunnel Sealing Experiment (Martino et al., 2001), as well as rock mass monitoring instrumentation used in the Mine-by Experiment (Read and Martin, 1996) have been documented. Acoustic emission (AE) and microseismic (MS) monitoring tools and techniques, and associated acoustic velocity surveys, have been used successfully at the URL and elsewhere to monitor the development of excavation damage and to assess characteristics of the EDZ (e.g., Young et al., 2004). Instrumentation performance for long-term monitoring has also been assessed at the URL (Martino, 1995). In general, the state-of-the-art in monitoring instrumentation is considered sufficient for short-term monitoring efforts, but new advances in technology (e.g., fibre-optic sensors) may improve robustness and longevity of instruments in harsh environments (e.g., Borgermans et al., 2004). Sedimentary rocks may represent different chemical environments that could affect instrument performance. In addition, layered sedimentary rock may interfere with geophysical instruments that rely on acoustic wave transmission through rock to estimate parameters or locate seismic source events. These issues require further study.

4.3.3 Summary - Rock Engineering in Construction/Operation

The role of rock engineering in the construction and operation of a DGR involves several activities:

- Excavation - Adapt DGR design specifications into a construction execution plan in conjunction with other disciplines (e.g., mining engineering, civil engineering, and construction). This involves evaluating different excavation methods and equipment, estimating productivity and equipment wear through specialized in situ and laboratory testing (tool-rock interaction studies), and analyzing potential effects of different excavation schedules and staging/sequencing options to minimize adverse effects on the rock mass around underground openings. It also entails developing procedures for incorporating results from excavation characterization into design modifications during construction.

- Ground support – Selection, design, implementation and monitoring of ground support systems is required to ensure worker safety during construction, and to preserve the integrity of the rock mass during construction and operation of the DGR. Some sedimentary rock types may pose particular challenges in terms of avoiding degradation effects on exposed rock surfaces, and ensuring long-term performance of bolting systems. Gas generation of metal bolting systems has been raised in previous conceptual designs as a potential issue, and may require additional study in the context of gas migration in sedimentary rock.

- Characterization – Conduct ongoing characterization of conditions and properties in excavations using techniques developed for the UCF, and update the geosphere model and rock mass classification of the excavations. This process is iterative and involves improving the understanding of rock mass conditions over the construction period. Back analysis of observed conditions also allows for improvements to predictive tools and techniques.

- Design modification – Update the design of specific repository panels and/or individual placement rooms based on results of excavation characterization conducted immediately following placement room excavation. This process involves conducting confirmatory analyses of potential effects using numerical tools developed for design analysis. This process could involve changes to the arrangement of panels and rooms to avoid potentially undesirable geological features, or changes to the positioning or spacing of placed UFCs in a particular room to avoid intersecting fractures. These types of modifications require a well-defined decision protocol to ensure design changes are not made on an ad hoc basis, and that as-built conditions are well documented.

- Sealing systems – In conjunction with other disciplines, develop detailed designs for sealing systems (including backfill, bulkheads, and grouting) and assess their potential interactions with the rock mass as the basis for establishing monitoring systems to gauge performance. In particular, swelling pressure exerted by the backfill on the rock mass is an important design element to ensure long-term stability and integrity of the near-field rock mass. Likewise, the integrity and effectiveness of sealing elements such as bulkheads and grouting of the rock-concrete interface, and their interaction with the rock mass, are important to long-term performance and safety (Figure 13). Remedial grouting of fracture zones and other potential hydraulic flowpaths may require further study in the context of specific sedimentary rock types to fully understand potential chemical and mechanical interactions.
- Monitoring – Monitor the rock mass during excavation activities and over the course of the construction and operations period to identify the possible development of damage around openings. Remote monitoring using AE and MS sensors is considered a preferred non-intrusive method to conduct monitoring of placement rooms. In addition, other strategically placed instruments are required to measure the performance of sealing systems. These instruments could include sensors to monitor displacement, temperature, pressure, and humidity, for example. Specific instrumentation requirements would be determined on the basis of rock mass response observed during development of the UCF. Ongoing management and analysis of monitoring data is also required.

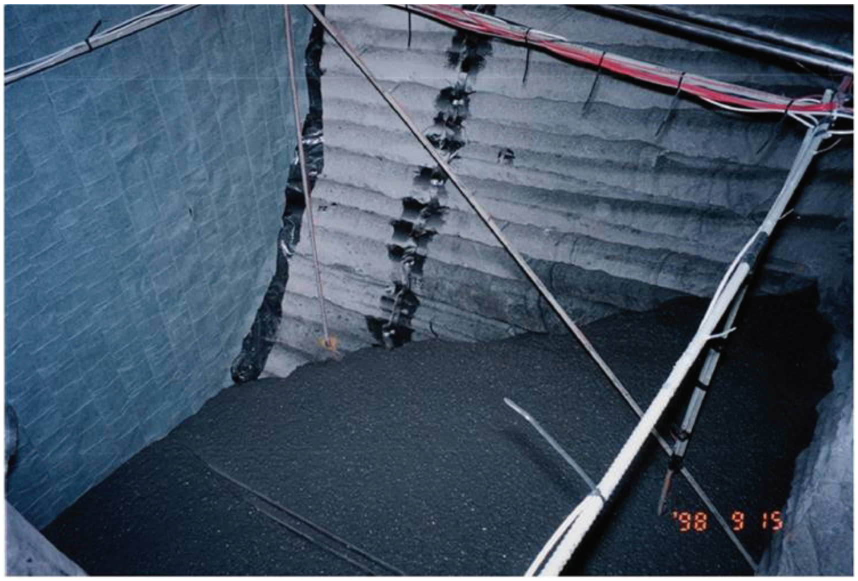


Figure 13: Rock-Concrete Interface in Tunnel Sealing Experiment Bulkhead Key (Chandler et al., 2002)

4.4 POST-CONSTRUCTION

Although beyond the terms of reference for this report, a brief overview of rock engineering aspects of the post-construction period is provided here for completeness. The main post-construction activities that involve rock engineering are extended monitoring prior to site closure, the design and implementation of sealing systems in access tunnels and shafts to finalize closure of the repository, and long-term post-closure monitoring (if required). If monitoring data indicate the need to retrieve placed UFCs, then additional rock engineering considerations may be introduced.

Extended monitoring (either pre- or post-closure) has been considered by Thompson and Simmons (2003). Given the long lead time for this activity, it is likely that technological advances in instrumentation will occur prior to DGR closure, and will require assessment and testing in conditions typical of a DGR in sedimentary rock. The layered nature of sedimentary rock may complicate the use of some remote monitoring techniques, and the interpretation of measured data.

Repository sealing systems have been discussed in general in AECL's EIS (AECL, 1994) in relation to the original DGR concept in granite. The concept was modified to account for an in-room placement design option (Baumgartner et al., 1995). A general conceptual view of an access tunnel sealing system is shown in Figure 14. This system includes grouting of fractured rock, fracture zones and interfaces, backfilling with clay- and/or cement-based materials, and concrete bulkhead construction at strategic locations. Borehole grouting is also included in this concept. Other concepts for tunnel seals (Figure 15) have also been proposed (USDOE/OCRWM, 2001). Important interactions in these systems occur along interfaces between rock, geomaterials, and concrete.

Hansen and Knowles (1999) describe a shaft sealing design for the Waste Isolation Pilot Plant (WIPP) site in layered rock. The shaft sealing system comprises 13 elements that completely fill the shaft with high density, low permeability engineered materials. The Salado Formation components provide the primary regulatory barrier by limiting fluid transport along shaft during and beyond the 10,000-year regulatory period in the USA. Components within the overlying Rustler Formation limit commingling between brine-bearing members, as required by state regulations. Above the Rustler Formation to surface, the shaft is filled with common materials of high density, consistent with good engineering practice. A similar concept for sedimentary rock in Canada may be suitable, but would require a similar design process to that used for the WIPP case.

The above examples illustrate that rock engineering has many roles, some primary and others secondary, over the life cycle of DGR. These roles span the pre- and post-closure phases of a DGR, and touch on all the major development stages, as well as post-construction.

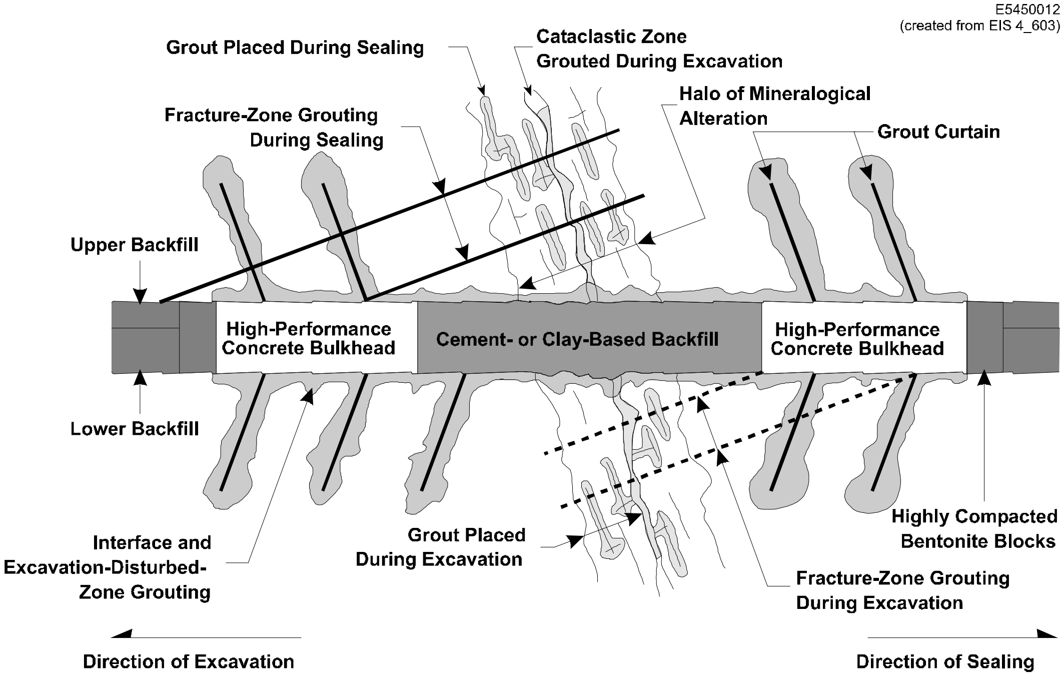


Figure 14: Conceptual Sealing System Components (Martino et al., 2001)

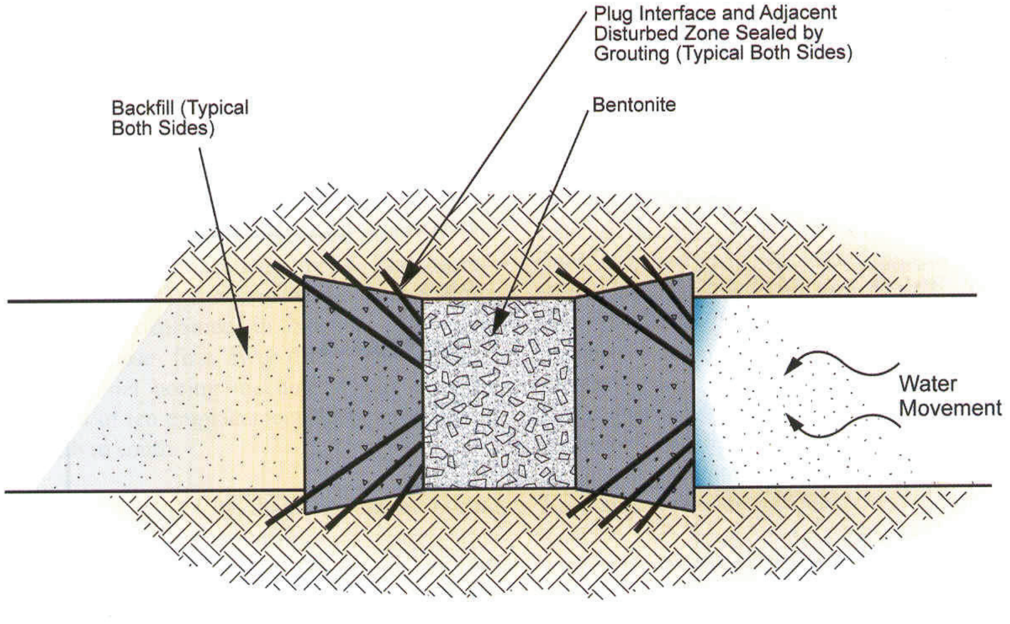


Figure 15: Conceptual Tunnel Plug Design (USDOE OCRWM, 2001)

5. INVENTORY OF ROCK ENGINEERING INFORMATION

Although the concept of sedimentary rock as a host medium for a DGR is not new, compared to the extensive research and development conducted on crystalline rock of the Canadian Shield, there has been less work done to advance this alternative concept in Canada. This section of the report provides a general inventory of rock engineering data, tools and techniques required to advance DGR development in sedimentary rock. It also summarizes available information relevant to rock engineering aspects of DGR development in the Michigan Basin. Additional information relevant to DGR development in sedimentary rock in Canada has been gathered in other international programs considering sedimentary rock as a host medium. Information from other areas of Canada comprising sedimentary bedrock is also available. Access to and review of all relevant existing data should be assigned a high priority in advancing this concept. The information in this report provides an initial basis for identifying and prioritizing rock engineering research and development objectives and related activities. Further detailed assessments are required to develop research and development plans in particular topic areas.

5.1 DATA REQUIREMENTS FOR DGR DEVELOPMENT

As described in Section 4 of this report, the data requirements for developing a DGR are linked to the various development stages, and therefore evolve over time. Geoscientific data needs from site characterization for development of a DGR in crystalline rock have been described in general terms by AECL (1994). A more detailed description of data requirements required to characterize sedimentary rock typical of the Michigan Basin in relation to a potential low/intermediate level DGR has been documented in a Geoscientific Site Characterization Plan (GSCP) (INTERA, 2006). The GSCP describes the geoscientific information needed to support the development of descriptive geosphere models and preparation of a DGR environmental assessment. The important DGR geoscience data needs in the GSCP include: geological setting and framework, geomechanical setting and framework, hydraulic properties and state, diffusion and sorption properties, groundwater/porewater characterization and seismicity. These categories also generally apply to a DGR for used fuel.

Table 2 contains information excerpted from the GSCP (INTERA, 2006) and consolidated to provide an overview of data requirements and the rationale and use for each parameter. Some of these requirements are not directly related to rock engineering, but may indirectly affect rock engineering decisions in DGR development. The information in Table 2 is based on the data needs for a specific site, and therefore may not include all data requirements for other specific sites within the Michigan Basin or those outside the Michigan Basin. Nonetheless, the contents of Table 2 are illustrative of the type of information required early in DGR development.

5.2 AVAILABLE ROCK MECHANICS INFORMATION

Within the Michigan Basin, the Ordovician Cobourg (Lindsay) argillaceous limestone and the Queenston shale represent potential DGR horizons. Information on general geology, geomechanical properties and in situ stresses for several Ordovician formations in the Michigan Basin has been compiled.

Table 2: Summary of Data Requirements for DGR Development (after INTERA, 2006)

Data Requirement	Rationale and Use
Geological Setting and Framework	
Existing Geological Information - Local and regional information on overburden, lithology and structure of bedrock units from ground surface to Precambrian basement - Basin geologic history including tectonics, sediment source, dissolution events, and thermochronology from time of sedimentation - Inventory of petroleum geology resources	- Provides regional geological framework for site characterization plan, baseline monitoring program to define background conditions, understanding of geologic homogeneity of deep Ordovician bedrock units, and understanding of long-term geologic stability of site. - Provides assessment of resource potential and likelihood of human intrusion scenario.
Existing Geophysical Information - Inventory of regional aeromagnetics and gravity surveys, existing 2-D and 3-D seismic surveys completed for oil and gas exploration investigations.	- Provides regional geological structural framework for site characterization plan. Regional seismic surveys may assist in evaluation of merit of completing site-specific surveys.
Stratigraphic Sequence, Formation Thicknesses and Attitudes - Overburden and bedrock units from ground surface to Precambrian. - Elevations of top and bottom of each unit/formation.	- Provides geometric framework for 3D geosphere model of DGR which is an integral part of facility performance assessment, design and safety case. - Uniformity of formation thickness and attitude can also support the safety case via predictable geology.
Structural Framework - Major faults/fracture zones and minor joints/fractures within 1 km of DGR in all bedrock units, particularly within Ordovician shales and limestones.	- Important for assessing potential for advective transport from DGR, and for assessing likelihood of earthquake-induced fracturing of host rocks for the DGR.
Bedrock Petrography and Mineralogy - Petrographic, mineralogic and elemental composition (U, Th, K, Ra Rb) of all bedrock units, including geochemistry of pore and fracture surfaces. - Identification of thermal diagenetic changes in mineralogy and secondary mineral precipitation changes to rock porosity.	- Provides identification of bedrock units, allows unit interpolation between holes. Necessary for reliable characterization of pore fluid chemistry, radionuclide sorption and retardation, isotope in-growth calculations (i.e., ^{129}I and ^{36}Cl), and estimation of natural background radioactivity (Ra, Rb).
Geomechanical Setting and Rock Properties	
Existing Geomechanical Information - Compilation and evaluation of geomechanics data (stresses, rock material properties and rock mass properties) from other excavations in these bedrock units.	- Important for providing context for required geomechanics testing, and indication of range of likely parameter variability and spatial variability within similar formations tested elsewhere.
In Situ Stress Regime - 3D stress tensors for Ordovician shales and limestones and overlying shales.	- Required for design of DGR openings (layout, dimensions, support) and for design of access and ventilation shafts.
Rock Material Properties - Suite of laboratory geomechanical tests of rock core from Ordovician shales and limestones and overlying shales including: standard index tests, strength and deformation parameters, anisotropy characteristics, creep parameters, swelling/squeezing parameters and thermal properties.	- Required for use throughout DGR design, construction and monitoring phases to evaluate responses of rock materials to changes in stress, geochemical regime, moisture content and temperature.
Rock Mass Properties - Geomechanical properties of overall rock mass including discontinuities and variably spaced shale partings. Focus on rock mass classification systems (Q, RMR, GSI) and geomechanical properties of discontinuities in host rock horizon; data needed for all bedrock units to be excavated.	- Required for engineering analyses, environmental impact assessment (waste rock disposal/reuse), and design of the DGR facility including DGR rooms and shafts.

continued…

Table 2 (continued)

Data Requirement	Rationale and Use
Hydraulic Properties and State	
Existing Hydrogeological Information - Hydrogeological properties of overburden and bedrock units from investigations undertaken at specific site and elsewhere in Ontario.	- Provides hydrogeological basis for assumed favourable geoscientific features and characteristics of site. - Provides indication of likely range of hydrogeological properties for deep bedrock units. Assists in design of proposed testing and sampling programs.
Rock Mass Hydraulic Properties - Spatial distribution and anisotropy of bulk rock mass permeabilities/storativities for all bedrock formations hosting and overlying/underlying DGR. - For Ordovician shales and limestones, the hydraulic properties of joints and shale partings or interbeds need to be quantified.	- Needed to quantify relative importance of advective versus diffusive transport properties, advective groundwater fluxes into/out of DGR, time to resaturate DGR; also needed to model groundwater flow and radionuclide transport as part of DGR performance assessment and Safety Assessment.
Hydraulic Heads - Transient and steady-state hydraulic heads within all bedrock formations.	- Needed to define hydraulic gradient fields within and between bedrock formations, and to model groundwater flow in performance assessment. Anomalous heads can also support safety case. - Transient head response both following casing installation and following shaft and DGR excavation can also be used to estimate bulk rock permeability and storage properties.
Total and Effective Rock Matrix Porosities - Intact rock total and transport porosity and porosity geometry for Ordovician and Silurian bedrock formations.	- Required for calculation of advective velocities from estimated Darcy fluxes, and to interpret pore matrix fluid chemistries derived from rock core. Larger interconnected matrix porosities in fractured rock units can contribute to the safety case through enhanced dispersion and retardation by matrix diffusion.
Fracture/Fault Hydraulic Properties - Transmissivity (T), storativity (S) and equivalent fracture aperture (2b) for important structural discontinuities (faults, fracture zones) near the DGR.	- Required to calculate advective groundwater and radionuclide migration rates within fracture pathways, if present.
Gas–Brine Flow Properties - Gas entry pressure (pressure at which gas can begin to displace brine from rock pores) and gas-brine relative permeability testing to assess gas migration into excavation damage zones and away from DGR.	- Required to model pressure buildup and dissipation rates for gases generated by corrosion and other processes in the DGR and to assess potential for host rock fracturing. Gas pressure buildup affects fluid flow to/from the DGR, as well as the mechanical response (closure) of the rock.
Groundwater Densities - Unit weight of groundwater due to dissolved gas and total dissolved solids, temperature, and pressure within each bedrock formation.	- Required to accurately assess effects of density on groundwater flow in numerical simulations of variable density groundwater flow. Can also contribute to safety case through demonstration of stagnant deep flow systems.
Diffusion and Sorption Properties	
Effective Diffusion Coefficients - De values for radionuclides of interest to Safety Assessment (e.g., ^{3}H, ^{129}I, ^{36}Cl,^{99}Tc, ^{90}Sr) in low permeability Ordovician shales and limestones in both vertical and horizontal directions. -Large scale De values may also be estimated from inverse modeling of formation specific isotope concentration profiles.	- Required as the current conceptual model assumes that migration within the Ordovician sediments is diffusion dominated.

continued…

Table 2 (continued)

Data Requirement	Rationale and Use
Diffusion and Sorption Properties (cont.)	
Effective Diffusion Porosities - Estimated at the same time as De values for radionuclides of interest in low- permeability Ordovician shales and limestones	- Required for assessment of diffusive migration in host rocks and surrounding low-permeability formations. This porosity estimate will provide a first approximation of the 'geochemical porosity' for geochemical modeling of pore-water chemistry.
Sorption Parameters - Retardation factors, adsorption isotherms and Kd for Sr and other weakly and strongly sorbed elements, in the Ordovician shales and limestones	- Retardation due to sorption will provide additional retention in the low permeability rocks immediately surrounding the DGR.
Groundwater/Porewater Characterization	
Existing Hydrogeochemical Information - Hydrogeochemical properties of overburden and bedrock units from investigations undertaken at specific site and elsewhere in Ontario.	- Provides indication of likely range of hydrogeochemical properties for deep bedrock units. - Provides baseline water quality information for local shallow bedrock water supply aquifer. Assists in design of proposed testing and sampling programs. - Provides indication of the properties of waste rock and of pumped out water/brines for use in Environmental Assessment (EA)
Major Ion and Trace Element Chemistry - Definition of the major ion and trace metal composition of porewater and groundwater within all bedrock and overburden units. - Baseline groundwater quality within the shallow bedrock aquifer on-site that serves as a local off-site water supply. - Natural stable iodine concentration in shallow bedrock aquifer to define maximum possible dose from ^{129}I. - Definition of quality of water to be pumped from the DGR - Master variables, pH and Eh, to allow charge balance calculations and geochemical modeling of the pore-water and groundwater chemistry - Cation exchange capacity (CEC) and exchangeable cations for Ordovician shales and limestones - Trace elements, e.g., Fe, Mn, U and As in porewaters and groundwaters	- Characterization of the major ion and trace element chemistry in shallow, intermediate and deep bedrock units can provide evidence of lack of cross formational flow and response to other flow perturbations within the deep Ordovician shale and limestone formations. - Necessary for the geochemical reconstruction of the pore-water chemistry of the Ordovician rocks, for use in EA (quality of water pumped from DGR), and for use in Safety Assessment (maximum possible dose from ^{129}I). CEC and the exchangeable cations will be measured to interpret porewater chemical evolution through geochemical modeling.
Isotope Chemistry - Data on ^{18}O, ^{2}H, ^{3}H, and ^{87}Sr and to lesser degree on ^{36}Cl, ^{14}C and ^{129}I in matrix porewaters and groundwaters - If fractures and fracture-filling minerals are detected in the Ordovician rocks in early testing, then additional solid samples will be tested for other isotopes, e.g., ^{13}C, ^{18}O and $^{87}Sr/^{86}Sr$ during later testing	- Required to provide information to demonstrate absence of modern recharge water and late Quaternary glacial water intrusion to deep shale and limestone formations surrounding DGR. Also this data may – under certain conditions – support residence times of >1,000,000 years through the acquisition of complementary information on minimum residence times.
Dissolved Gases - Data on He, Ar, Ne and N_2 dissolved gas contents and isotopes of porewaters and groundwaters in bedrock units. See Redox States below.	- Necessary to confirm diffusion-dominated mass transport profiles, and to estimate water residence times and ages through He, Ar, N_2, and $^{3}He/^{4}He$, $^{40}Ar/^{36}Ar$ and Ne isotope ratios.

continued…

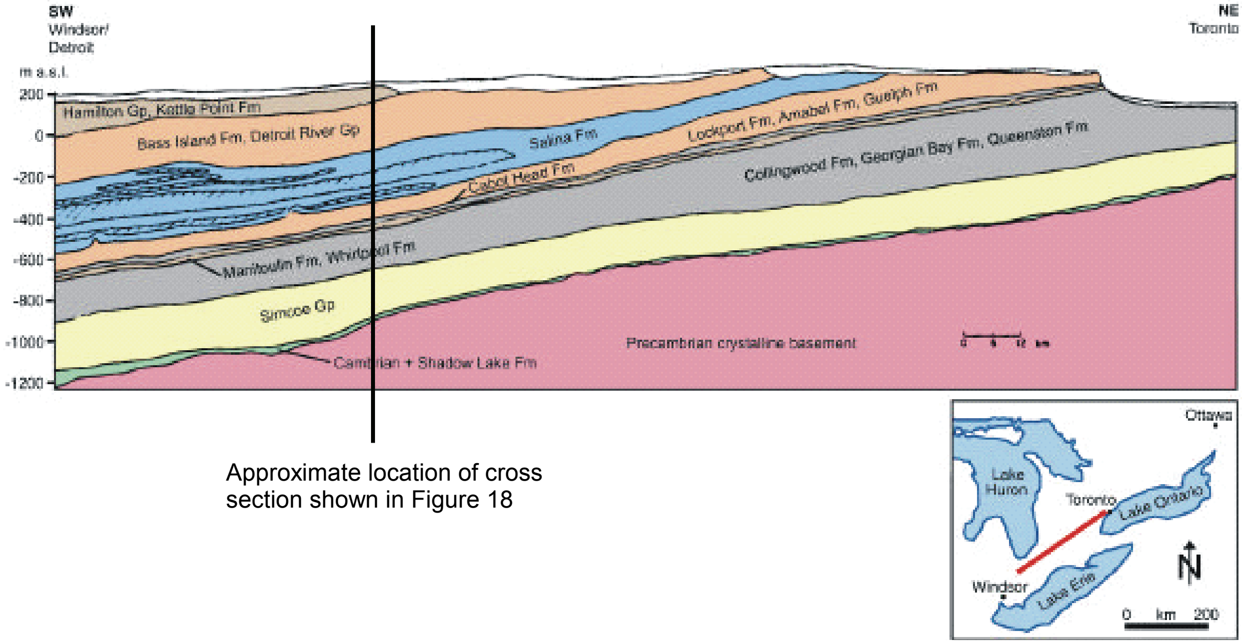
Table 2 (concluded)

Data Requirement	Rationale and Use
Groundwater/Porewater Characterization (cont.)	
Redox States - Estimation of approximate redox potential of porewaters and groundwaters by measurement of Eh (i.e., measured Pt electrode potential),); gases such as CH_4 and H_2S; redox-sensitive trace elements such as Fe, Mn, As, U; and geochemical modeling involving redox pairs such as sulphate-sulphide and bicarbonate-methane	- Important for identification of redox state of principal radionuclides for use in geochemical modeling to reconstruct pore-water chemistry and to predict future redox conditions and radionuclide speciation.
Water Physical Properties - Viscosity and temperature of pore waters and groundwaters.	- Necessary as rates of diffusion and advection are a function of density, viscosity and temperature.
Seismicity	
Map Significant Local Faults - Identification and mapping of all significant faults and fracture zones within 1 km of the DGR.	- Required for assessment of potential for seismic-induced rupturing of DGR along or as splays of pre-existing structural discontinuities and/or the presence of potential pathways or boundary conditions for numerical flow system simulation.
Local Seismographic Monitoring - Seismicity data from additional seismograph stations for 5 years and for and additional 5 years to confirm results.	- Improved local seismographic monitoring (within 50 km of the specific site) will improve the correlation of microseismicity with specific local and regional structural features, improve estimates of earthquake focal depths, and improve estimates of local seismicity.

5.2.1 General Geology

The general geology and geotechnical characteristics of the rock of the Michigan Basin have been described by Mazurek (2004). Southern Ontario is located along the southeastern rim of the North American Craton. The crystalline basement rocks in this area are overlain by the Paleozoic sedimentary rocks of the Western St. Lawrence Platform. The SW-NE trending Algonquin Arch in the crystalline basement in the central part of this area separates the Michigan Basin to the northwest and the Appalachian Basin to the southeast. As shown in Figure 16, the general stratigraphy of southern Ontario comprises Paleozoic formations of Cambrian to Devonian (543 - 354 Ma) age. These stratigraphic units are near-horizontally bedded and are only weakly deformed. They include shales, limestones, dolomites, sandstones and evaporites (salt, gypsum/anhydrite) of the Michigan and Appalachian sedimentary basins, and reach a maximum thickness of about 1500 m in Figure 16.

Mazurek (2004) identifies the Middle/Upper Ordovician age (ca. 470 – 443 Ma) shales (Blue Mountain, Georgian Bay and Queenston Formations) and underlying limestones (Simcoe Group) as potentially suitable bedrock formations for a DGR. These formations are laterally continuous throughout large regions of southern Ontario. As shown in Figure 16, the stratigraphic sequence dips gently to the SW, with salt of the Salina Formation above the deeper Queenston Formation shale and Lindsay Formation limestone over much of the section. The subsurface Lindsay Formation is equivalent geologically to the Cobourg Formation exposed in outcrop in parts of the Michigan Basin. Near the Bruce Nuclear site at Tiverton, Ontario, the limestones of the Middle Ordovician Cobourg, Sherman Fall, Coboconk and Kirkfield Formations underlie the Upper Ordovician shales. The Cobourg Formation comprises



Approximate location of cross section shown in Figure 18

Figure 16: Stratigraphic Section Through the Michigan Basin (Mazurek, 2004)

argillaceous limestone while the Sherman Fall Formation comprises interbedded limestones and shales.

A simplified lithostratigraphic profile based on conditions near the Bruce site is shown in Figure 17. The Queenston Formation shale (about 450 to 650 m depth) is described as a reddish-brown shale (mudstone) with occasional interbeds and nodules of green siltstone (less than 30% of green siltstone in the upper beds). The red colour (iron oxide) reflects a marine deltaic deposit. The Lindsay Formation limestone (about 650 to 840 m depth) is described as a very fine grained to lithographic, non-porous, argillaceous to shaly limestone of very consistent lateral continuity. This unit has been mapped near surface as horizontally bedded with horizontal fractures spaced 0.5 to 1 m, and vertical fractures spaced 10 m (Golder, 2003). At depth, fracturing may be less common. The Cobourg and Sherman Fall Formations are of equivalent age to the Lindsay Formation. It should be noted that depths of these units vary along the section line in Figure 16 due to variations in surface topography and thickness of surficial deposits. For the sake of this report, conceptual DGR depths are 500 m in shale, and 750 m in limestone.

5.2.2 Fracture Characteristics and Seismicity

Sanford et al. (1985) have identified major lineaments separating crustal blocks in southern Ontario. One major lineament runs from the Georgian Bay coast line southeast toward the Toronto area. A second lineament runs SW-NE beneath southern Ontario, roughly coinciding with the Algonquin Arch, and terminates against the first lineament. These lineaments bound the Bruce Megablock in the northwestern part of southern Ontario and the Niagara Megablock in the southeastern part. These blocks are considered as units with a partly independent tectonic evolution dominated by periodic basement reactivation (Mazurek, 2004).

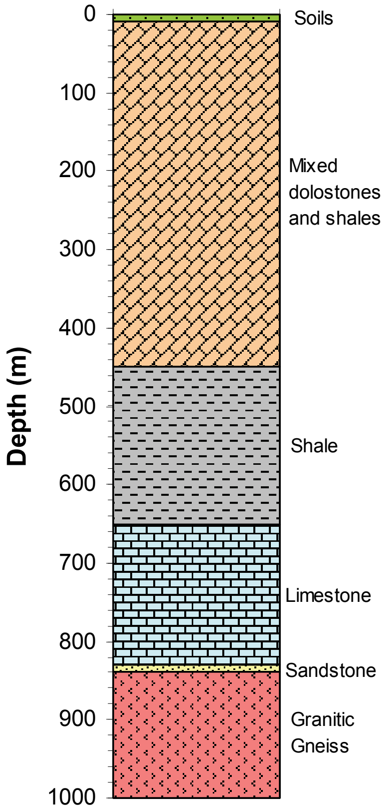


Figure 17: Simplified Lithostratigraphic Section of Michigan Basin (after Golder, 2003)

The large-scale fracture pattern in the Bruce Megablock inferred by Sanford et al. (1985) is relatively simple compared to that in the Niagara Megablock. The length of the major fractures lies in the range of tens to hundreds of kilometres, and their spacing is 10 to 30 km. Details on smaller scale fracturing are limited to specific study areas; further studies on repository-scale fracturing at potential DGR sites are required as part of site characterization (INTERA, 2006).

Historic earthquakes are rare in the Bruce region (Adams and Halchuk, 2003). Synsedimentary faulting in southwestern Ontario is attributed mainly to relative movements along basement faults between the Algonquin Arch and the basins on either side. Salt dissolution in the Upper Silurian Salina Formation has produced salt collapse structures in the overlying Silurian and Devonian strata in some areas (Mazurek, 2004). According to Golder (2003), the sub-erosion of the Salina salts from beneath the Bruce Site has structurally influenced the entire overlying rock sequence through collapse and differential subsidence. This has resulted in warping of the overlying strata, development of vertical fracturing and possible enhancement of formational permeability extending through the Devonian sequence. This fracturing phenomenon should therefore be considered as part of site evaluation during the technical siting process.

5.2.3 Unique Aspects of Sedimentary Rock

Sedimentary rocks considered for a DGR have some unique aspects. Carbonates and anhydrite may be susceptible to karsting (i.e., the dissolution of rock and development of cavities within the rock mass) under certain groundwater flow conditions. In limestone and dolomite, mild carbonic acid produced from CO_2 in the atmosphere and soil is primarily responsible for the solvent power of flowing groundwater on carbonate rocks. Over time, carbonate aquifers change from diffuse-flow aquifers with water moving as laminar flow through small openings, to conduit-flow aquifers with water moving primarily as turbulent flow through well-developed conduit systems to discharge points at springs (Figure 18). Certain carbonate traps are targets for oil and gas drilling. Anhydrite units (e.g., Salina salt) are particularly sensitive to groundwater flow, as illustrated by salt collapse structures in the Michigan Basin. These units require special attention in the development of a DGR to avoid undesirable long-term effects.

Shales also have some unique characteristics. They may exhibit swelling or time-dependent volume increase involving physico-chemical reaction with water; marine shales are particularly susceptible to this effect. As well, osmotic effects and shale hydration (i.e., flow caused by gradient in ionic species concentration) are common borehole stability issues in oil and gas drilling. In underground openings, desiccation and slaking behaviour is common due to wetting/drying cycles and ventilation effects, and can result in rapid deterioration of the exposed rock. The effects on elastic properties and strength can be significant, particularly on weak interfaces/bedding. Shale is also typically viewed as a potential caprock for oil and gas reservoirs due to its low permeability to water and gas. The possibility of trapped gas therefore should be considered in planning and executing drilling and excavation campaigns.

Figure 18: Example of Karst Development in Limestone (R. Read)

5.2.4 Rock Mass Properties

Two sources of rock property data were considered in preparing this report. Lam et al. (2007) provide a compilation of geomechanical properties for Paleozoic bedrock formations in southern Ontario based on an NWMO database of over 700 geomechanical test measurements from 29 sites in southern Ontario. Properties for typical Michigan Basin rock types were previously provided by Baumgartner (2005) and other unpublished reports. Reconciliation of these two data sets was not undertaken as part of this report, but is a necessary future step in developing a reference geosphere model for candidate areas and potential sites. The specific units identified by Lam et al. (2007) represent a more detailed stratigraphic description than that provided by Baumgartner (2005), but the general stratigraphy is consistent on a gross scale. In some cases, the specific formation names given by Lam et al. (2007) are local variants of those shown in Figure 16. The NWMO geomechanical properties database lists the geologic age, elevation, depth, group, formation and local equivalents for each entry where available.[6]

The test results summarized by Lam et al. (2007) include unconfined compressive strength (UCS), triaxial compressive strength, direct tensile strength, Brazilian (split) tensile strength and shear strength of bedding partings. Based on the compiled geomechanical properties (Table 3), the mean unconfined compressive strength (UCS) of the Cobourg argillaceous limestone is 72 MPa, whereas the Sherman Fall interbedded limestones and shales have UCS values of 116 and 51 MPa, respectively. The direct tensile strengths of both the Cobourg and Sherman Fall Formations are low at about 1 MPa, compared to 6 MPa obtained from Brazilian (split tension) tests, likely due to anisotropy from weak bedding partings. A regression analysis of triaxial test results with the Cobourg argillaceous limestone from Darlington and Bowmanville area derived a material constant *m* of 10.3 for the Hoek-Brown failure criterion. For the Coboconk and Kirkfield Formations, the estimated value of *m* is 27.8. Shear tests on Sherman Fall Formation rock produced a friction angle of 32°.

Lam et al. (2007) note that the NWMO geomechanical properties database for sedimentary rocks contains additional unreported information. Review of the database indentified compressional wave velocity, dynamic elastic modulus, porosity and absorption as additional parameters. Some rock samples also differentiate between vertical and horizontal elastic modulus and Poisson's ratio values as an indication of anisotropy. Cross plots of unconfined compressive strength (UCS) and several measured parameters (P-wave velocity, elastic modulus, and effective porosity) are shown in Figures 19, 20 and 21. Correlations between UCS and P-wave velocity, and between UCS and elastic modulus, presented by Lam et al. (2007) show general trends but correlation coefficients are less than 0.6 in both cases. No correlation was found between UCS and effective porosity. These correlations do not differentiate values by rock type. Further analysis of the NWMO database may reveal stronger correlations by rock type. Analysis results should be updated as new data are added to the database.

Previous estimates of rock mass properties (e.g., Baumgartner, 2005) for the various lithologic units in the generalized stratigraphic profile shown in Figure 17 are summarized in Table 4. These values were derived primarily from Golder (2003) based on limited testing of representative samples from outcrop. The data are extrapolated from known sites with similar

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[6] Variations in geological names of formations and units from location to location are important to recognize in order to correlate information on rock properties and in situ stress. See INTERA 2006 for an example of reconciliation of formation names near the Bruce site.

Table 3: Summary of Geomechanical Properties of Michigan Basin Formations (Lam et al., 2007)

Rock Formation		UCS (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Density (g/cm^3)
Amherstburg Dolomite	Mean	63 (4)		27 (6)		
	Range	33 – 113		8 - 40		
Amherstburg Limestone	Mean	74 (9)		31 (11)		
	Range	23 – 182		12 - 66		
Eramosa	Mean	118		63	0.4	
	Range					
Goat Island	Mean	210 (10)		67 (6)	0.3 (6)	
	Range	137 – 282		58 - 81	0.2 - 0.4	
Gasport	Mean	142 (26)		57 (12)	0.3 (13)	
	Range	27 – 255		25 - 70	0.1 - 0.5	
Decew	Mean	107 (5)	5	54 (5)	0.4 (4)	
	Range	74 -174		43 - 57	0.3 - 0.4	
Irondequoit	Mean	105 (11)		60 (11)	0.4 (11)	
	Range	60 – 185		50 - 78	0.1 - 0.5	
Reynales	Mean	107 (13)		33 (11)	0.4 (3)	
	Range	53 – 141		22 - 49	0.2 - 0.5	
Cabot Head	Mean	73 (7)	9 (22)			
	Range	20 -127	5 - 14			
Queenston	Mean	44 (50)	10 (4)	15 (47)	0.4 (48)	
	Range	12 -118	1 -15	7 - 34	0.1 -0.5	
Georgian Bay	Mean	35 (63)		9 (49)	0.3 (39)	
	Range	3 – 206		1 - 58	0.1 - 0.5	
Collingwood	Mean	52 (12)		14 (5)	0.2 (3)	
	Range	27 – 132		2 - 31	0.2 - 0.3	
Cobourg	Mean	72 (94)	1 (15)	32 (94)	0.3 (72)	2.7
	Range	22 – 140	0.04 - 2	10 - 67	0.1 - 0.6	2.6 – 2.9
Sherman Fall (*shale and **limestone)	Mean	51 (13)* 116 (31)**	1 (7)	40 (19)	0.3 (7)	2.7
	Range	23 – 69* 71 – 161**	0.1 - 3	1 -73	0.1 - 0.4	2.5 – 2.7
Coboconk & Kirkfield	Mean	59 (13)		40 (5)	0.4 (5)	
	Range	37 – 83		15 - 61	0.2 - 0.8	
Gull River	Mean	131 (5)		68 (5)	0.3 (5)	
	Range	90 – 189		62 - 71	0.3 – 0.4	
Shallow Lake	Mean	88 (2)	5	28 (2)	0.3 (3)	
	Range	77 – 99		28 - 29	0.2 - 0.4	

(x) Number of test results included in calculation of mean value.

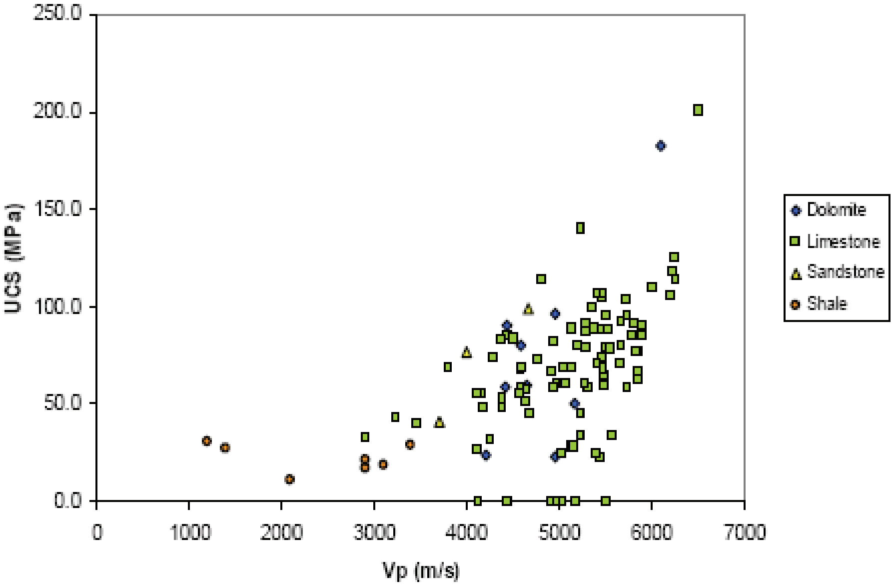

Figure 19: UCS vs P-Wave Velocity for Michigan Basin Ordovician Rock (Lam et al., 2007)

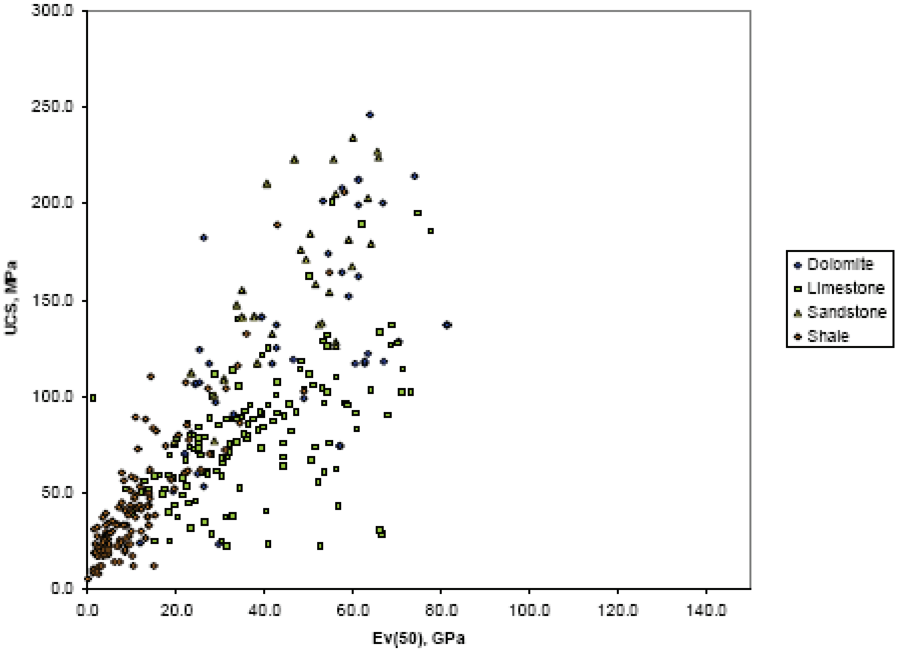

Figure 20: UCS vs Young's Modulus for Michigan Basin Ordovician Rock (Lam et al., 2007)

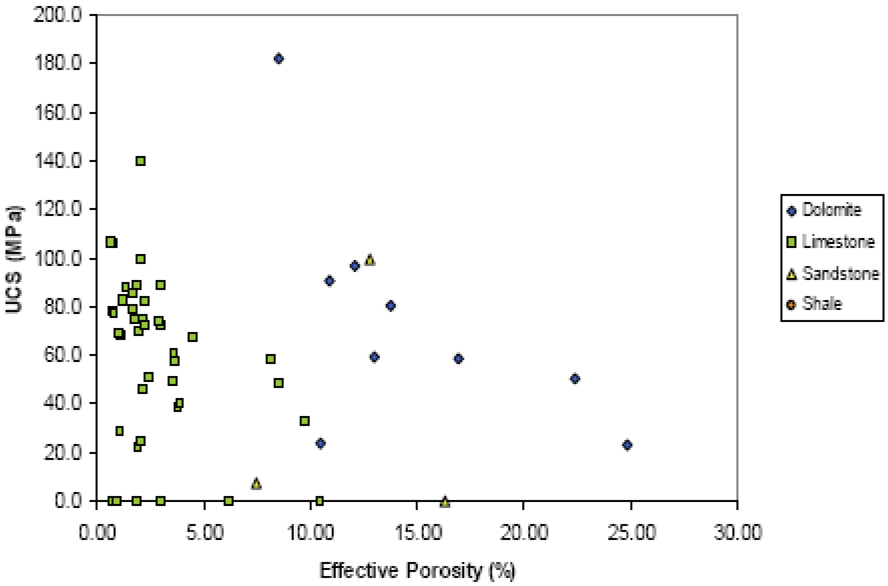

Figure 21: UCS vs Effective Porosity for Michigan Basin Ordovician Rock (Lam et al., 2007)

stratigraphy in southern Ontario to the area around the Bruce site. It is noted that properties of many of the stratigraphic units are unknown (N/A in Table 4). Table 4 provides information on other key rock properties such as thermal conductivity, specific heat, and thermal expansion coefficient required for thermal-mechanical analysis. Values for the Hoek-Brown parameter *s* are also provided. Queenston Formation shale and Lindsay Formation limestone have respective rock mass classification values of 11 and 32 for Tunnel Quality Index (Q), and rock mass rating (RMR) values of 65 and 75 (Golder, 2003) based on outcrop mapping. These values correspond to Good Rock (Rock Mass Class 2). The corresponding Geological Strength Index (GSI) values (Hoek et al., 1995) are 66 and 74 for the two units, respectively. The low values of the Hoek-Brown parameter *s* in Table 4 suggest that both rock types are jointed.

It is noted that the Hoek-Brown *m* parameter values in Table 4 are significantly less than the values determined by Lam et al. (2007). Conversely, unconfined compressive strength and tensile strength values determined by Lam et al. (2007) are generally greater than those in Table 4, while elastic modulus and Poisson's ratio values are similar. The discrepancies in parameter values in Table 4 relative to Table 3 are likely a result of extrapolation of data from other sites to the Bruce site. While the data in Table 4 are considered sufficient for preliminary scoping analyses to support siting, the discrepancies in values illustrate the importance of obtaining site specific information for DGR design purposes.

A thorough review of the existing data in the NWMO database and its relation to the values in Table 4 would allow consolidation of information for future analyses. It is noted that other parameters required for future detailed design analyses (e.g., Biot's coefficient, fracture toughness, creep parameters, and anisotropic moduli and strength parameters for some units) are not reported. These should be measured on fresh core samples to minimize effects of core deterioration. Results from downhole geophysical logging should also be reported to supplement the current database of rock properties, and allow comparison of results obtained from core to those obtained from the borehole. This last step provides a means of identifying core sample damage.

Table 4: Thermal-Mechanical Properties for Rock Types of the Michigan Basin (Baumgartner, 2005)

Properties	Soils	Mixed Dolostones and Shales	Shale	Limestone	Sandstone	Granitic Gneiss
Dry Density (Mg/m^3)	1.8	2.6	2.6	2.6	2.6	2.8
Porosity (%)	30	7	11	2	0.5	<0.4
Young's Modulus (GPa)	N/A	N/A	12 (6-23)	40 (16-66)	N/A	60 (est.)
Poisson's Ratio	N/A	N/A	0.3 (0.1–0.44)	0.3	N/A	N/A
Uniaxial Compressive Strength (MPa)	N/A	N/A	40 (33-46)	60 (25-140)	N/A	N/A
Tensile Strength (MPa)	N/A	N/A	3 (2-4.6)	N/A	N/A	N/A
Hoek-Brown *m* Parameter	N/A	N/A	4.26	3.89	N/A	N/A
Hoek-Brown *s* Parameter	N/A	N/A	0.0221	0.0529	N/A	N/A
Thermal Conductivity (W/(m·°C))	1.5	2.3	2.1	2.3	2.5	3.0
Specific Heat (J/(kg·°C))	1500	920	975	830	810	810
Thermal Diffusivity (m^2/a)	N/A	N/A	N/A	N/A	N/A	N/A
Coefficient of Thermal Expansion (°C)$^{-1}$	N/A	N/A	2×10^{-6}	6.7×10^{-6}	N/A	10×10^{-6}

(Source: Baumgartner 2005 and unpublished source)

5.2.5 Temperature

Estimated temperature conditions for thermal-mechanical analysis of the Michigan Basin are summarized by Baumgartner (2005). A geothermal gradient of 0.019°C/m depth, with an assumed mean annual surface temperature of 7°C, is considered representative of this region. Based on this gradient, the calculated ambient rock temperature of the repository level at 500 and 750 m depth is 16.5 and 21.3°C, respectively. To account for possible continental glaciation, the mean annual surface temperature was reduced to 0°C beyond 10,000 years in previous analyses (CTECH, 2002), and this condition was assumed to persist from 60,000 to over 105,000 years. In situ temperature measurements in boreholes drilled to characterize rocks in the Michigan Basin are required to confirm these assumptions.

The rock mass above the repository level will expand and heave as the repository level is heated, creating a decrease in the near-surface lateral stresses. The near-surface lateral stresses will become tensile given sufficient heave, creating a zone of lateral extension. The tensile strength limit of this zone is conservatively set to zero to account for the influence of near-surface fracture systems. As part of design considerations for a DGR in crystalline rock, a limit of 100 m was set for the maximum depth of the near-surface extension zone relative to ground surface (Baumgartner et al., 1995).

5.2.6 In Situ Stresses

Site-specific in situ stress measurements in the various stratigraphic units in the Michigan Basin at a potential DGR site have not been reported. However, regional stress data (Adams and Bell, 1991; Reinecker et al., 2004) suggest that within the area east of the Canadian Cordillera, the maximum horizontal stress σ_H is larger than the vertical stress σ_v. In this area, σ_H trends ENE to NE. Overcoring tests in the uppermost 2 km of the Precambrian basement show that the minimum horizontal stress σ_h often exceeds σ_v, although not consistently (Mazurek, 2004). Consequently, stress conditions most frequently correspond to those of a thrust faulting regime (Engelder, 1993).

Overcoring and hydraulic fracturing tests have been conducted in the sedimentary rocks of the St. Lawrence Platform to a depth of about 300 m at various locations (Adams and Bell, 1991). Shallow overcore tests within 70 m of ground surface show considerable scatter, with the maximum and minimum horizontal stresses typically larger than the vertical stress. Hydraulic fracturing tests conducted between 70 and 300 m depth (Figure 22) show a similar pattern. Scatter in the data for the maximum horizontal stress is possibly due to stress variations across stratigraphic units, with stiffer rock types carrying more stress than softer rock types. This pattern suggests a tectonic contribution to the in situ stress state at some locations. Recognizing that these data are sparse and representative of only the specific sites from which they were obtained, the general trends in the hydraulic fracturing data suggest that the horizontal stress components may be roughly approximated by the following equations:

$$\sigma_H = 0.0208 \cdot z + 12.3 \text{ MPa} \tag{1}$$

$$\sigma_h = 0.0246 \cdot z + 4.7 \text{ MPa} \tag{2}$$

where *z* is the depth in metres.

Assuming that the vertical stress is lithostatic, the estimated initial stress conditions at the conceptual repository depths based on the stratigraphic section in Figure 16 and the specific stratigraphic column shown in Figure 17 are as follows:

- For a repository level at 500 m depth in the Queenston Formation shale, the estimated stress conditions are σ_H = 23, σ_h = 17, and σ_v = 13 MPa. This implies far-field stress ratios of σ_1/σ_3 = 1.7 and σ_2/σ_3 = 1.3.
- For a repository level at 750 m depth in the Lindsay Formation limestone, the estimated stress conditions are σ_H = 28, σ_h = 23, and σ_v = 20 MPa. This implies far-field stress ratios of σ_1/σ_3 = 1.4 and σ_2/σ_3 = 1.2.

Measured horizontal stress values of 9 to 13 MPa in the Lindsay Formation limestone, and 5 to 9 MPa in the Queenston Formation shale at depths less than 200 m (Golder, 2003) suggest that stiffer limestone carries higher stresses than softer shale. Consequently, the horizontal stresses calculated from Equations 1 and 2 may be over- or under-estimated. It should be

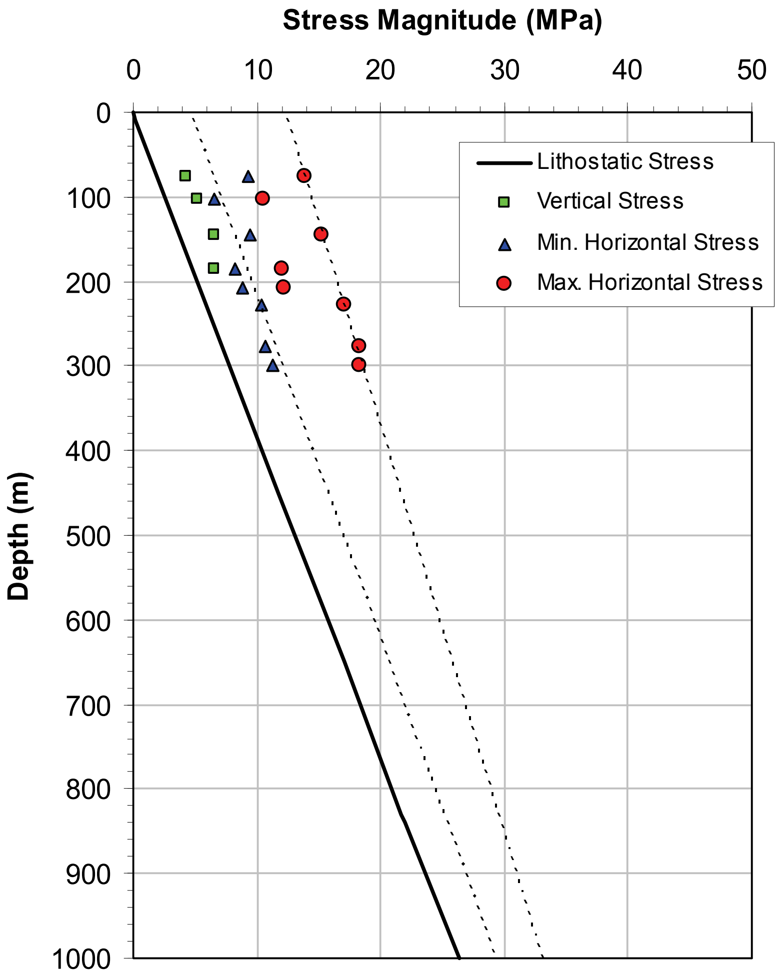

Figure 22: Comparison of Stress Measurement Results and Lithostatic Stress Profile for the St. Lawrence Platform (after Adams and Bell, 1991)

noted that these stress measurements were conducted at locations where these units are relatively close to surface, therefore extrapolation of these data to greater depths is tenuous. Likewise, the published data on stress measurements are not specific to a particular area, and raise some questions regarding the measurement and analysis techniques used to derive these data. Although the relations represented by Equations 1 and 2 are used for the purposes of this report, reliable stress measurements at a DGR site are considered essential to support these and more detailed future analyses.

In keeping with the data requirements prescribed in Table 2, NWMO is developing an in situ stress database for sedimentary rock of the Michigan Basin. The database at the time of writing included 183 stress measurements, including 124 overcore measurements and 59 hydraulic fracture measurements from 28 sites in southern Ontario and northern USA. Figure 23 provides a summary of the stress measurements available in the NWMO stress database by rock type. Figure 24 provides a summary of results. Of these measurements, the total number

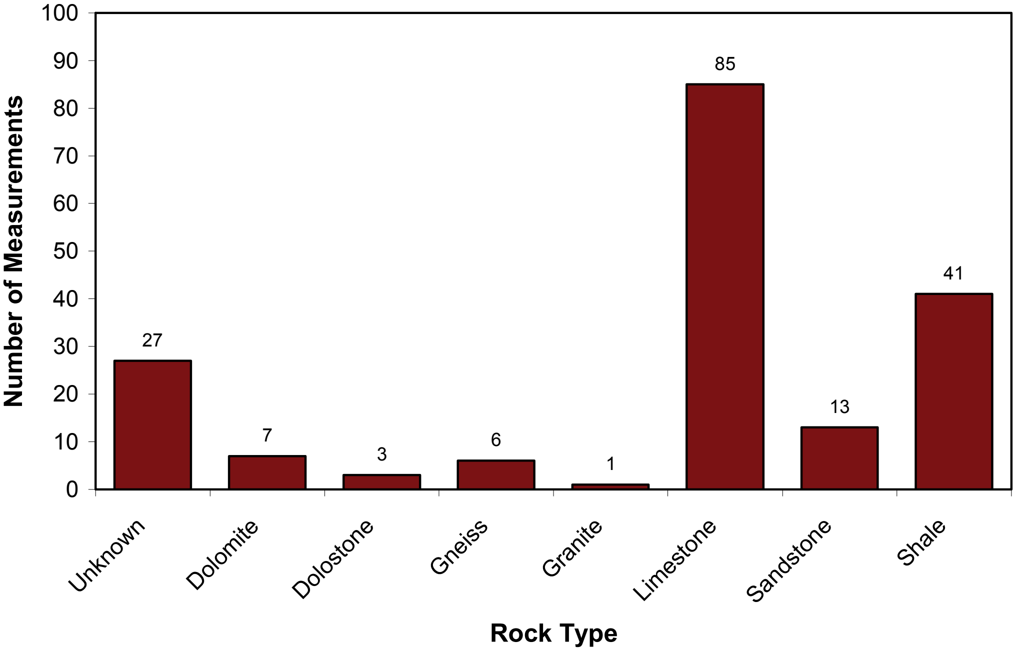

Figure 23: Summary of Stress Measurements in NWMO Database by Rock Type

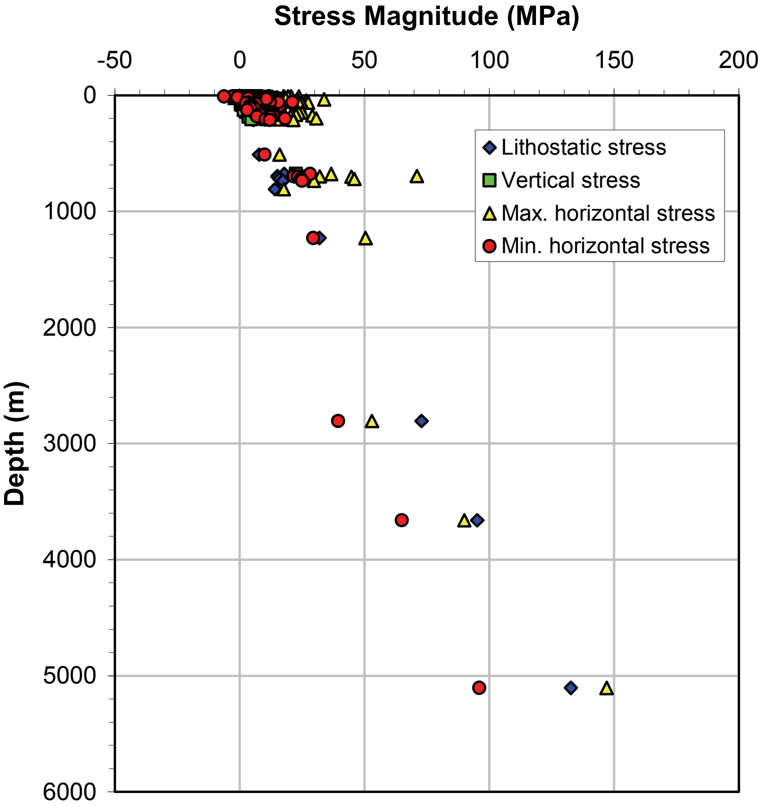

Figure 24: Stress Measurement Results in NWMO Database (All Rock Types)

related to σ_H, σ_h, and σ_v is 180, 164, and 42, respectively. In all cases, one of the principal stresses was assumed to be vertical; no stress orientation other than azimuth of σ_H was reported. One measurement of σ_H at 23 m depth, and nine measurements of σ_h between 4 and 23 m depth, were negative (i.e., tensile). Measured σ_v values were generally similar to, or greater than, the reported lithostatic stress values. The lithostatic stress values were calculated using different relations depending on location, and therefore show considerable scatter.

Lam et al. (2007) reported on the findings of in situ stress measurements in the NWMO database from 25 of these sites in southern Ontario and northern USA. The compiled data from overcoring and hydraulic fracturing indicate high compressive stress in Paleozoic bedrock formations. At a potential DGR depth of 660 m considered by Lam et al. (2007), the stress ratio, σ_H/σ_v, was estimated to be about 2.0 to 2.5, and the ratios σ_h/σ_v and σ_H/σ_h were estimated to be approximately 1.5. Based on these stress ratios, for an assumed overburden stress of 17 MPa, the maximum and minimum horizontal stress magnitudes at a depth of 660 m are approximately 35 and 25 MPa, respectively. Regional stress data from 1000 to 6000 m depth based on unpublished reports were included in the analysis by Lam et al. (2007).

To extend the analysis of the NWMO stress database, separate datasets for stress measurements in limestone and shale were extracted (Figure 25). Zero values were removed from each dataset, then a linear regression analysis was performed. Based on the available data in the NWMO stress database, the maximum and minimum horizontal stress gradients for limestone are more than double those for shale, with similar non-zero x-intercept values. In contrast, the lithostatic stress relations for the two rock types are quite similar.

These findings suggest that rock types with different elastic properties may carry different horizontal stresses resulting from tectonic activity. In this case, the stiffer limestone appears to carry higher horizontal stresses than the shale. The horizontal stress magnitudes and stress ratios for limestone are significantly greater than the blended stress values derived from Equations 1 and 2 used for general scoping analyses (e.g., Read, 2008). Further analysis of the stress results is required before drawing conclusions, as the base data are from different locations and different formations. Nonetheless, the example in Figure 25 suggests that sedimentary rock sequences may have more complex stress regimes than other more homogeneous rock types, and may therefore require more intensive stress characterization activities. In turn, general scoping analyses may need to consider a broader range of possible stress magnitudes and stress ratios for different rock types depending on expected tectonic history and rock stiffness at a site. Other information, such as the plunge and trend of each stress component, may also have implications for rock engineering if principal stresses are not horizontal and vertical. Qualification of existing and future stress measurement results through review of individual overcore and hydraulic fracture test information (if available), and critical review of derived values, is essential to improve confidence in the stress database.

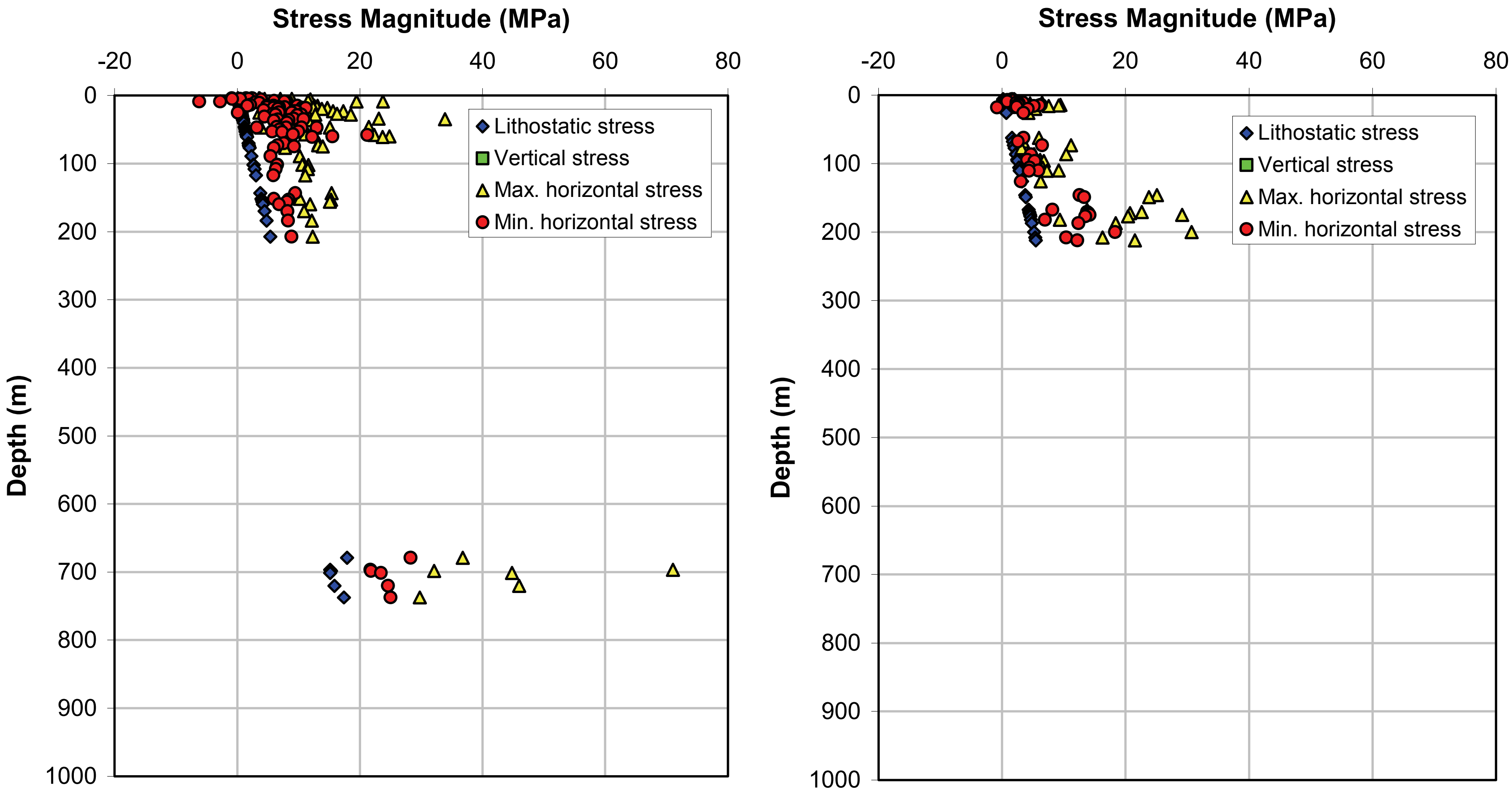

Figure 25: Comparison of Stress Measurement Results for Limestone (Left) and Shale (Right) in NWMO Database (Data Point at 5105 m Depth in Shale Not Shown)

5.2.7 Pore Pressure

Hydraulic head in boreholes penetrating Upper Ordovician to Middle Silurian strata (Queenston to Guelph Formations) of the Niagara region has been investigated (Novakowski and Lapcevic, 1988) to derive a pore pressure profile with depth. Hydrostatic pressures were found in the Guelph Formation within 60 m of ground surface. All underlying units to a maximum depth of 150 m show over- or under-pressures of 20 to 50 m (i.e., above or below hydrostatic head). Under-pressures are likely due to hydraulic connection of dolomite aquifers to exfiltration areas at lower elevation in the Niagara Gorge. Over-pressures are at least partially related to low permeability units such as the Rochester Shale. The largest vertical hydraulic gradients often occur along lithologic contacts to shales such as the Queenston Formation, suggesting very low vertical hydraulic conductivity in these units. Gas migration below shale caprock also accounts for some over-pressures in southern Ontario. Although the actual pore pressure conditions for the Queenston and Lindsay Formations probably vary considerably with distance from the Niagara Gorge, it is likely that they range from hydrostatic to values up to about 1 MPa above hydrostatic in the lower permeability shales. Based on the unit weight of water and with reference to Figure 17, the hydrostatic pore pressure at 500 m depth in shale is calculated to be 4.9 MPa. At 750 m depth in limestone, the hydrostatic pore pressure is calculated to be 7.4 MPa.

5.2.8 Glaciation Effects

Glaciation effects have been considered in previous analyses in the same fashion as for the crystalline rock scenario, applying a surload equivalent to 3000 m of ice to the ground surface after 10,000 years (CTECH, 2002). Based on an ice density of 920 kg/m^3, this adds about 27 MPa to the vertical stress below ground surface. Assuming an average Poisson's ratio of 0.3, the associated increase in horizontal stress in the rock is expected to be $\Delta\sigma_v\ (\nu/(1-\nu))$ = 12 MPa.

Depending on the shape of the glacial front, the leading edge of the advancing glacial ice may generate high shear stresses, and possibly promote near-surface fracturing (similar to bearing-type failure near the edge of a footing). This effect is attenuated with depth as the σ_V/σ_H stress ratio decreases beneath the applied load. Near-surface freezing and eventual thawing may help to disaggregate the rock mass. Depending on the rate of advance of the glacial ice, excess pore pressures may also be generated. These are considered near-surface effects. Confirmatory analysis would help quantify the depth to which they may extend.

5.3 TOOLS AND TECHNIQUES

Geoscientific site characterization of crystalline rock for a DGR, along with general characterization tools and techniques, has been described by AECL (1994). A more detailed description of the tools and techniques required to characterize sedimentary rock typical of the Michigan Basin was reported in the GSCP (INTERA, 2006). The GSCP provides a technical description of the selection and proposed application of preferred tools and techniques for site-specific geoscientific characterization. These tools and techniques have been linked to geoscience data needs, and consider results of previous detailed geoscientific studies completed in the Michigan Basin, and recent international experience in geoscientific characterization of similar sedimentary rocks for radioactive waste isolation purposes. The GSCP also describes complementary geoscientific studies considered necessary to develop a comprehensive geoscientific understanding of a selected site relevant to the DGR safety case. The GSCP report (INTERA, 2006) is considered an excellent example for future planning purposes, and for undertaking characterization of potential DGR sites in sedimentary rock. The approaches and rationale outlined in the GSCP can be applied in sedimentary rocks in other areas outside the Michigan Basin. Appendix B contains excerpted information from the GSCP (INTERA, 2006) related to characterization tools and techniques.

Rather than reiterate all aspects of tools and techniques covered in the GSCP and Section 4 of this report, the following sections provide insights into a few considerations unique to sedimentary rocks to be taken into account in developing a DGR.

5.3.1 Drilling and Sampling

Some sedimentary rocks, such as shales, are particularly susceptible to sample handling damage, or damage that occurs due to desiccation. Therefore, sampling handling and preparation procedures are extremely important, as is the choice of drilling fluid, to avoid swelling, deterioration and contamination of the rock sample. Drilling fluid specialists should be engaged at the early stages of designing a drilling program.

For most geomechanical testing, intact or fractured test samples are preferred over reconstituted or powdered samples. Specialized drilling equipment, including split-tube triple-tube core barrels, is one method to retrieve intact samples. The choice of drill bit and drilling method are important considerations, and may change as different strata are encountered. Photography of core in the split tube immediately upon retrieval is one method to record the rock condition prior to subsequent handling and other damage. Desiccation can be avoided by putting samples in split PVC tube, and using plastic, tinfoil and wax to seal samples.

These aspects are discussed in some detail in the GSCP (INTERA, 2006).

5.3.2 Standard Laboratory Testing

The principal laboratory tests required to characterize the properties and behaviour of sedimentary rock include the following:

- Physical property and index tests to measure initial moisture content, saturation, density, mineralogy, grain size, hardness, and porosity; tests to determine typical P- and S-wave velocities of samples are also used for correlation to other properties.
- Mechanical property tests may include uniaxial and triaxial compression, direct tension, Brazilian (split tension) test, direct shear tests, oedometer tests, creep tests, slake durability tests, and fracture toughness tests. These tests are conducted at various temperatures to assess strength/deformation trends with temperature. Free-swell or oedometer tests measure swelling potential using simulated pore water and distilled water; stiff shales with high smectite content may have high swelling potential.

- Thermal property tests are required to measure specific heat, thermal conductivity, thermal diffusivity, and thermal expansion coefficient of samples. This latter parameter is extremely important for thermal-mechanical analyses.
- Hydraulic tests to determine hydraulic conductivity, Biot's coefficient, relative permeability (gas and water), and capillary pressure are also required.

From experience in crystalline rock, it is important to establish characteristic short- and long-term rock properties from laboratory tests, including measurements of crack initiation stress, crack damage stress, peak strength, ultrasonic velocities, static and dynamic Young's modulus and Poisson's ratio under a range of isotropic and deviatoric stress conditions (Lau, 1999). Relationships for time-to-failure as a function of rock type, confining stress and temperature should be developed using approaches similar to those of Lau et al. (2000). Fracture toughness testing and crack velocity testing (Lajtai and Bielus, 1986) are characterization tests that could be used to calibrate numerical models. Correlations between static and dynamic elastic dynamic properties should be determined and these data compared with similar correlations for crystalline rock (e.g., Eissa and Kazi, 1988).

These tests and other standard tests are described in the GSCP (INTERA, 2006) and by Read and Chandler (2002).

5.3.3 Other Testing

As described in Section 4, there is a suite of specialized laboratory tests required to characterize specific aspects of material behaviour. These tests include the following:

- Damage-controlled loading tests using loading/unloading cycles to track damage development under ambient and elevated temperature
- Long-term loading tests (static fatigue) to measure time-dependent strength behaviour under ambient and elevated temperature
- Thermoporoelasticity tests to derive THM coupling parameters
- Tests on rock joints to assess coupled stress-flow response (M-H)
- Downhole geophysical logging using standard oil field tools to measure in situ properties and conditions
- Other mechanical tests may include abrasion and tool-rock interaction tests to assess tool wear potential.

Other specialized tests may be required to assess specific aspects of sedimentary rock behaviour or characteristics, such as anisotropy. The thermoporoelastic characteristics of the rock are particularly important, and should be determined from laboratory tests (Lau et al., 1999) and in situ tests (Martino and Chandler, 1999; Berchenko et al., 2004). Scoping thermoporoelastic calculations should be conducted on a conceptual repository configuration (Detournay and Berchenko, 2001; Detournay and Senjuntichai, 2001) to determine the potential for thermally induced hydraulic fracturing in the rock.

Some of the foreseeable in situ tests required to quantify rock mass behaviour and characteristics include:

- Excavation response tests to measure deformation, in situ stress, stress change, pore pressure change, damage development, and progressive failure around horizontal openings at the repository level, and around vertical excavations in other rock types (e.g., AECL's Mine-by Experiment). These can be conducted at different scales to assess scale effects using different sized boreholes up to full-scale excavation. Alternate tunnel shapes can be tested to assess stability implications (e.g., AECL's Excavation Stability Study).
- Thermal-mechanical tests to assess the rock mass response around an excavation to temperature increase in the absence of ground support or backfill, and with backfill to assess the effects of confining stress on damage development (e.g., AECL's Heated Failure Test). These can be conducted at different scales to assess scale effects using different sized boreholes up to full-scale excavation.
- Thermal-hydraulic tests to assess possible thermoporoelastic effects, and to back analyze THM coupling parameters (e.g., AECL's Thermal-Hydraulic Experiment)
- Mechanical tests to measure in situ moduli (e.g., flatjack tests).
- Hydraulic tests to measure in situ hydraulic properties of the rock mass and fracture/fault zones.
- Sealing system tests to assess the performance of bulkheads and borehole seals under high differential hydraulic pressure, and under ambient and elevated temperature conditions, such as the Tunnel Sealing Experiment (Chandler et al., 2002).
- Grouting trials in high permeability zones to assess effectiveness of grouting tools and technology, and to develop grouting materials and methodologies.

Read and Chandler (2002) provide other examples of in situ testing, and propose three in situ validation tests, to be conducted as part of DGR development. These and other in situ tests may be required to fully characterize rock mass behaviour over a range of boundary conditions.

6. DISCUSSION

This report provides a broad overview of the role of rock engineering in DGR development in sedimentary rock. It is not intended to be an exhaustive gap analysis or a detailed plan such as the GSCP. Given the relatively early stages of research and development on sedimentary rock as a potential host medium for a DGR in Canada, this report provides a starting point for identifying and prioritizing rock engineering aspects of the DGR development process, and related research and development activities.

Technical and scientific research activities are envisioned in three general areas (NWMO, 2005):

- Research involving site-specific investigations into the technical performance of the management system.
- Research on the characteristics and performance of geology potentially suited to implementation of the selected management approach. While much is already known about crystalline rock, further research is required to understand the

suitability and technical requirements of sedimentary rock in relation to implementing Adaptive Phased Management.

- Continued monitoring and engagement in research being conducted internationally to further the understanding of social, technical and ethical considerations.

This latter point is of particular interest as there are a number of national research programs actively pursuing DGRs in sedimentary rocks (e.g., France, Switzerland, Japan, and Spain). Active participation in these national radioactive waste management programs, and attendance at key information exchanges such as meetings, conferences, and technical workshops, is considered vital with respect to developing a DGR in sedimentary rock in Canada. Such participation is in keeping with the original recommendations of the 1977 Hare report.

The development and application of numerical modeling tools is an ongoing area of research that would benefit from international experience. A bonded particle model for crystalline rock using the code PFC produced promising results in sparsely fractured crystalline rock in terms of tracking damage development and progressive failure of the rock mass. Several recommendations regarding the use of PFC in DGR design were put forward in the Thermal Mechanical Stability Studies final report (Read and Chandler, 2002), and are valid for a DGR in sedimentary rock. New advances in the use of PFC have been made since completion of that report. The use of particle clustering algorithms to improve the simulation of strength envelope is one example of a recent advance (Potyondy and Cundall, 2004). In addition, advances in the use of other numerical codes such as FLAC have been made (e.g., the incorporation of Biot coefficient in FLAC). The recent work by Diederichs (2007) is a good example of advances in the rock mechanics research that directly benefit the technical community, and are applicable to the issue at hand – developing a DGR in sedimentary rock.

The rock properties database for sedimentary rocks of the Michigan Basin (Lam et al., 2007), particularly for the Queenston Formation shale and Lindsay Formation limestone, is an excellent start in developing a broad understanding of sedimentary rock properties and rock mass conditions. This is considered the first step in a broader review of geomechanical properties and conditions in rock formations that meet general DGR siting criteria proposed by Mazurek (2004). A thorough understanding of rock properties and rock mass conditions in areas both within and outside the Michigan Basin is important in advancing the technical siting process. A detailed analysis of the NWMO geomechanical properties database would help identify information gaps and provide the basis for a strategy to bridge the identified gaps.

Likewise, the NWMO database of in situ stress measurements from the Michigan basin is a good start in understanding stress conditions in potential host sedimentary rock basins. A thorough review of available stress measurement results would be beneficial to qualify available data, and screen out potentially questionable results. For example, a review of hydraulic fracturing as a stress measurement tool (Thompson et al. 2002) suggests that estimates of horizontal stress components using this method are subject to many uncertainties associated with the stress measurement method. Similarly, overcoring results may be affected by inelastic and or non-linear rock responses, particularly rock damage occurring during overcoring stress relief. Review of the actual test data would be required to assess the quality of results, but is a valuable step if such information is available. In addition, in situ stress data derived in the preparation of regional and local stress models based on known structural geology should be compiled (e.g., Tonon et al., 2001), and information cited by Mazurek (2004) should be reviewed and added to the database if not already included.

The continued development of a comprehensive in situ stress database is expected to be expanded to cover areas of potentially suitable sedimentary rock in other regions of Canada. This requires review of measurements not only over a large geographical area, but also at different depths to develop a clear understanding of stress gradients with depth. Experience in the Canadian Western Sedimentary Basin, for instance, suggests that horizontal stress magnitude may vary considerably from one stratigraphic unit to the next, resulting in a stepped stress profile. The data reviewed as part of this report suggest a similar situation may exist in the Michigan Basin and, by inference, other sedimentary basins. This has significant implications in terms of accurately estimating in situ stress conditions and the potential for shearing along interfaces between rocks of different stiffness. Weak horizontal shear zones at the base of major shales units represent a potential challenge to DGR design. It is also unlikely for principal stresses in the Michigan Basin to be horizontal and vertical given the nature of the stratigraphic section in Figure 16. The plunge of the major principal in situ stress will be a factor in design and therefore should be determined.

Other unique aspects of sedimentary rock that may pose design challenges are potential karst development in limestones and anhydrites, swelling behaviour in clay-rich rock, sensitivity to fresh water of some marine shales, osmotic effects during drilling, susceptibility to wetting/drying and desiccation, and anisotropic properties (Figure 26).

Figure 26: Example of Layering in Dolomitic Limestone Resulting in Anisotropic Properties (R. Read)

7. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this report was to provide an overview of the role of rock engineering in the siting, design and construction of a DGR in sedimentary rock. The review also considered the data, tools and techniques required to advance DGR development. Available information on rock mechanical properties and in situ stress measurements for the Michigan Basin was included in the review.

Based on the information in this report, it is concluded that rock engineering will play an important role in each stage of DGR development, and during post-construction. This report provides a basis for prioritizing the various rock engineering aspects of DGR development, and initiating research and international collaboration to advance capabilities and information required for the siting, design and construction of a DGR in sedimentary rock in Canada.

It is further concluded that sedimentary rock, while imposing similar requirements for DGR development as crystalline rock in some respects, has some different rock engineering requirements in relation to characterization, testing, monitoring, and design analysis. Given the stratified nature of sedimentary rock basins, the level of characterization of rock properties, in situ stress, pore pressure and other conditions is significantly more intense (i.e., more measurements are required) compared to more homogeneous rock types. The presence of multiple interfaces between different rock types also increases the complexity of the geological/geotechnical model and associated characterization and modeling requirements. This geological complexity may also affect the application of some monitoring options. Other unique aspects of certain sedimentary rocks (e.g., shales and anhydrites) pose additional rock engineering challenges. These complexities affect engineering design and construction, including excavations, ground support and sealing systems.

Given the relatively limited research and development efforts related to DGR development in sedimentary rock in Canada, it is recommended that the information in this report be used to develop and prioritize research and development plans related to rock engineering. Some specific activities to be considered are as follows:

- Conduct a thorough review of all data in the NWMO sedimentary rock properties database to identify gaps and additional data requirements, confirm proposed correlations, and conduct ongoing literature review and data extraction from public and private sources to supplement the database with information from potential candidate regions of Canada. This review should consider relevant information on the unique aspects of shales and carbonates (e.g., karsting potential) in relation to excavation design and stability.
- Conduct a similar review of the NWMO in situ stress database with an eye to qualifying the collected measurements, identify gaps in coverage, correlate stress values to rock properties, and conduct ongoing literature review and data extraction from public and private sources to supplement the database with information from potential candidate regions of Canada. Information on pore pressure distributions should also be compiled to allow calculation of effective stresses.
- Review recent advances in numerical modeling tools capable of geotechnical material analysis and assess their applicability to design analysis for a DGR in sedimentary rock. In particular, conduct a thorough literature review on the use of

numerical codes to design stable openings with minimal excavation damage, and define a development plan for testing and application of numerical tools and techniques. Seek collaborative opportunities with other national waste management organizations pursuing similar research to benefit from their experience in sedimentary rock.

- Review recent advances in monitoring instrumentation and assess applicability of tools and techniques for monitoring a DGR in sedimentary rock. Specifically, conduct a literature review on monitoring tools and techniques that can be used in conditions associated with a DGR in stratified sedimentary rock, identify limitations, and seek collaborative opportunities with other national waste management organizations to bridge the identified gaps. Recent advances in fibre-optics instrumentation should be investigated as part of this review.

- Review recent advances in laboratory and field testing and assess applicability of tools and techniques for characterizing rock engineering properties required for development of a DGR in sedimentary rock. Undertake preliminary testing of rock samples to determine if findings for crystalline rock regarding rock strength and stress relations can be adapted for sedimentary rock. Identify limitations and gaps in laboratory and field testing procedures, tools and techniques, and seek collaborative opportunities with other national waste management organizations to bridge the identified gaps.

- Review and document engineering design issues anticipated for development of a DGR in sedimentary rock based on the various design concepts described in this report. Develop a plan for addressing these design issues. The plan should consider the following activities:

    - Continue participation in international experimental programs and projects related to specific rock engineering issues (e.g., the Rock Shear Experiment at Äspö HRL), and pursue new opportunities in this regard in Japan, Europe and elsewhere where large-scale testing is planned. The details of such projects are considered valuable in either planning similar tests in Canada, or incorporating international lessons learned into our understanding of sedimentary rock mass behaviour.

    - Conduct a thorough review of pillar stability issues in sedimentary rock to assess the implications on excavation design.

    - Assess implications of findings of this report in relation to an optional shallow underground storage facility.

- Participate in international meetings and conferences to maintain ongoing technical information exchange related to rock engineering research and development.

ACKNOWLEDGEMENTS

The author wishes to thank Neil Chandler and Sean Russell for their efforts in reviewing this report. Their comments are very much appreciated.

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APPENDIX A: SUMMARY OF ORIGINAL AECL DGR DESIGNS

Table A.1 Summary of AECL In-Floor Borehole Conceptual DGR Design

Component	Description
Shafts	Five vertical concrete-lined shafts ranging from 3.95 to 7.9 m excavated diameter, accessing a service shaft complex and an upcast shaft complex at opposite sides of the used fuel placement area.
Access Tunnels	A pair of horizontal central access tunnels connecting the two complexes and providing central access through the repository, with eight pairs of perpendicular horizontal access tunnels to service eight used fuel placement room panels, and a series of perimeter access tunnels connecting the panel access tunnels and the service shaft complex. The central and perimeter access tunnels are rectangular with dimensions 6 m wide by 5 m high. The placement panel access tunnels are 6 m wide and 6.5 m high.
Placement Rooms	Placement rooms are rectangular with an arched roof. Each room is 8.0 m wide with a height ranging from 5.0 m at the sidewall to 5.5 m at the centre of the room, and a length of 230 m. Placement rooms are spaced 30 m apart centreline-to-centreline, with a calculated extraction ratio of 0.267 (slightly higher than the target 0.25). There are 64 rooms per panel for a total of 512 placement rooms.
Placement Boreholes	Vertical boreholes 1.24 m in diameter and 5.0 m deep are drilled in the invert of each placement room at a centre-to-centre grid spacing of 2.1 m. There are 282 placement holes per room in three parallel lines. A total of 144,384 boreholes are required.
Used Fuel	Each fuel bundle consists of 37 used fuel elements and is about 495 mm long and 102 mm in overall diameter. Each bundle has a mass of 23.74 kg and contains 18.93 kg U, with an assumed burnup rate of 685 GJ/kg U (190 MW·h/kg U). For an assumed cooling period of 10 years out-of-reactor, the heat output is about 4.13 W/bundle.
Used Fuel Container	The used fuel container (UFC) is assumed to be a 6.35 mm thick particulate-packed titanium shell with nominal diameter of 645 mm and height of 2246 mm. Each container can accommodate 72 used fuel bundles. For an assumed cooling period of 10 years out-of-reactor, the heat output is about 297.36 W/container. Specified maximum design temperature on outside surface of the placed container is 100°C.
Waste Inventory	191,000 Mg of uranium in the form of 10.1 million used fuel bundles placed in approximately 140,136 UFCs.
Repository Footprint	Single level of placement rooms with overall footprint of approximately 2.0 km by 2.0 km assuming ideal geologic conditions

Table A.2 Summary of AECL In-Room Placement Conceptual DGR Design

Component	Description
Shafts	Five vertical concrete-lined shafts ranging from 3.95 to 7.9 m excavated diameter, accessing a service shaft complex and an upcast shaft complex at opposite sides of the used fuel placement area.
Access Tunnels	A pair of horizontal central access tunnels connecting the two complexes and providing central access through the repository, with perpendicular horizontal access tunnels to service eight used fuel placement room panels, and a series of perimeter access tunnels connecting the panel access tunnels and the service shaft complex. The central and perimeter access tunnels, as well as the placement panel tunnels, are rectangular with dimensions 10 m wide by 4.4 m high.
Placement Rooms	Placement rooms are elliptical in cross-section, nominally 7.3 m wide and 3.0 m high, with a length of 238 m. Placement rooms are spaced 30 m apart centreline-to-centreline, with a calculated extraction ratio of 0.25. There are 64 rooms per panel for a total of 512 placement rooms.
Placement Cavities	Containers are placed horizontally in a mass of precompacted buffer blocks, associated sealing materials and structures. Containers are placed two abreast at 2.21-m centre-to-centre spacing and at a longitudinal spacing of 2.7 m. There are 158 containers per room for a combined total capacity of 80,896 containers.
Used Fuel	Each fuel bundle consists of 37 used fuel elements and is about 495 mm long and 102 mm in overall diameter. Each bundle has a mass of 23.74 kg and contains 18.93 kg U, with an assumed burnup rate of 720 GJ/kg U (200 MW·h/kg U). For an assumed cooling period of 10 years out-of-reactor, the heat output is about 4.58 W/bundle.
Used Fuel Container	The used fuel container (UFC) is assumed to be a 25.4 mm thick particulate-packed copper shell with nominal diameter of 860 mm and length of 1189 mm. Each container can accommodate 72 used fuel bundles. For an assumed cooling period of 10 years out-of-reactor, the heat output is about 330 W/container. Specified maximum design temperature on outside surface of the placed container is 90°C.
Waste Inventory	110,000 Mg of uranium in the form of 5.8 million used fuel bundles placed in 80,707 containers.
Repository Footprint	Single level of placement rooms with overall footprint of approximately 2.0 km by 2.0 km assuming ideal geologic conditions

APPENDIX B: DATA DETERMINATION METHODS

The tables in Appendix B are modified excerpts from INTERA (1996)

Table B.1 Geological Setting and Framework

Data Determination Method

Existing Geological Information

- Published maps and reports from Ontario Geological Survey (OGS), Ontario Ministry of Natural Resources (MNR) and Geological Survey of Canada (GSC) on quaternary and bedrock geology, bedrock structure, drift thickness and bedrock topography; structural surface and isopach maps of key formations; dolomitized fault zones and other geologic structures in the deep sedimentary sequence; well locations and electronic geological logs for all oil and gas wells
- Geophysical logs of selected wells from data brokerages in Calgary.
- Much of the available geologic data has already been compiled by Golder (2003) and by Mazurek (2004). Special additional attention to role of dolomitized fault zones in Trenton Black River Group and potential presence salt horizons in Salina Formation is required

Existing Geophysical Information

- Oil and gas exploration 2D and 3D seismic refection surveys from data brokerages in Calgary
- Regional aeromagnetic total field and gravity surveys for site area from GSC and OGS
- Bathymetric surveys of large lakes from OPG and Canadian Hydrographic Service (CHS) to support lake-based seismic surveys
- Existing seismic reflection data may be too distant from specific site and not cost-effective for use in the site characterization.

Stratigraphic Sequence, Formation Thicknesses and Attitudes

- Borehole drilling and core logging including continuous collection of rock core using wireline techniques, and on-site logging by a geologist for changes in lithology. Allows for visual inspection of rock. Provides the only tangible evaluation of geological environment without larger excavations. Obtain photographic record of all core.
- Borehole geophysical testing involves lowering geophysical tools down borehole after drilling and collecting measurements pertaining to rock properties; permits differentiation of stratigraphic units. Information represents properties within a limited distance from the borehole wall, except for some cross hole surveys if boreholes are spaced relatively close to each other (i.e., ~ 100 m). Tools useful for identification of stratigraphic sequence and formation thickness and attitude include:
  - Gamma – Records amount of gamma radiation emitted by rock surrounding the borehole andinfers varying clay content
  - Spectral Gamma – detection of gamma radiation emitted from formation used to differentiate potassium, uranium and thorium content to infer lithology based on clay mineral content
  - Gamma-Gamma (Density) – measurement of electron density obtained by exposing formation to gamma radiation from a source on probe to infer lithologic contacts and porosity
  - Neutron (Porosity) – measurement of hydrogen content by exposing formation to neutrons from a source on probe to infer lithologic contacts, water content and porosity
  - EM-Induction (Resistivity) – records electrical conductivity (resistivity) of rock and water surrounding the borehole which are effected by porosity and clay content of rock and TDS of porewater
  - Conductivity – measurement of variations in electromagnetic field induced by a transmitter in probe used to infer lithology from electrical conductivity (i.e., water/clay content)
  - Full Waveform Seismics – measurement of compressional, shear and Stoneley seismic velocities using probe source(s) and detectors (transducers)
  - Vertical Seismic Profiling (VSP) – measurement of shear and compressional seismic velocities using surface source and borehole detectors (geophones) to calculate bulk modulus and infer general rock competence and lithology
  - Cross Hole Seismic Profiling (Tomographic Survey) – measurement of shear and compressional seismic velocity of the formation between two boreholes, one of which contains sources(s) and the other detectors(s); used to determine general rock competence (i.e, bulk modulus)

Table B.1 (continued)

Data Determination Method

Stratigraphic Sequence, Formation Thicknesses and Attitudes (continued)

- 2D seismic surveys where variations of travel time for sound waves produced by explosives, vibrating plates, and air guns (sleeve guns) to be reflected and measured by receivers can indicate changes in lithology at a particular depth. 2D seismic surveys have receivers oriented in a line. These surveys produce information over a larger area than boreholes and can offer more detail by simply reducing the spacing between receivers and geophones. They are minimally intrusive but usually require borehole information and borehole vertical seismic profiling to improve interpretation. Changes in reflection rates of sound waves indicate a change in material properties (i.e., density) but do not indicate the lithology, this information must be inferred from core collected while drilling and from vertical seismic profiling of boreholes. These surveys can indicate the level of continuity of larger reflective features such as tops of formations, major bedding planes and other flat-lying stratigraphic features. Cannot directly identify strata or features dipping greater than 45 degrees
- 3D seismic surveys are similar to 2D surveys, however, receivers are oriented in a grid format (i.e., multiple 2D seismic lines with offset lines that are orthogonal to each other) which allows for a 3D interpretation of the data. Produces information over a larger area than boreholes and can offer more detail by simply reducing the spacing between receivers and geophones. The collection of data over offset lines and on an orthogonal grid generates a 3D interpretation of bedrock layering and structure. Similar to 2D surveys they cannot directly identify strata or features dipping greater than 45 degrees. They are also minimally intrusive but usually require borehole information and borehole vertical seismic profiling to improve interpretation. More steeply dipping strata or features require interpretation of vertical offsets in sub-horizontal layering. Coverage may be limited by surface infrastructure.
- Mineralogical data - see Table B.1 (Bedrock Petrography and Mineralogy)

Structural Framework

- Borehole drilling and core logging including: continuous collection of rock core while drilling; logging by on-site geologist for bedding plane contacts between different layers and structural features such as faults, fractures zones, smaller fractures or joints; logging water producing/losing zones as drilling progresses. Allows for visual inspection of rock, breaks in the core, and any chemical alterations on fracture surfaces which indicates hydraulic activity at some time. This is the only tangible evaluation of geological environment without larger excavations. Interpolation is required for extending structure between boreholes. Sampling of vertical structure is limited in vertical to sub-vertical boreholes. Unless borehole is drilled at a sub-vertical angle there is difficulty in orienting the core and therefore the core fractures. Mechanical breakage of core during collection process is sometimes difficult to differentiate from natural features, and may affect RQD estimates.
- Borehole geophysical testing involving: Lowering geophysical tools down borehole after drilling is complete and collecting measurements of rock mass and fracture properties; allows identification of structures intersecting or near boreholes. With the exception of borehole radar and tomographic cross-hole seismic surveys, identification is limited to the immediate vicinity of borehole. Tools useful for structural identification and mapping include:
  - Acoustic Televiewer – highly detailed measurement of borehole diameter obtained by timing the return reflection of an acoustic pulse of the borehole wall back to the probe; primarily used to infer fractures and their orientation, borehole diameter and borehole orientation
  - Optical Televiewer – collects an oriented image of the borehole wall which undergoes “restoration” to correct for optical distortion and creates a “virtual core”; primarily used for fracture location but also provides some lithologic information
  - FMI – Formation Macro Imaging, provides a high resolution image of the borehole wall that is of superior quality to that provided by optical or acoustic televiewer. This is an oil and gas tool requiring a 160 mm diameter hole
  - Video – video camera (VHS and SVHS) recording down length of borehole; used to visually inspect locations of fractures and voids, and large water movement zones
  - Caliper – mechanical measurement of borehole diameter based on the extension of 3 or 4 caliper arms
  - Borehole-Radar Reflection – records the reflected wave amplitude and transit time of high-frequency EM waves using a pair of downhole transmitting and receiving antennae; used to determine the location and dip of fractures and lithologic changes and to estimate the radial extent of such features beyond the borehole (3 to 10 m radial penetration dependent on the electrical resistivity of the rock and water surrounding the borehole)
  - Cross Hole Seismic Profiling (Tomographic Survey) – measurement of shear and compressional seismic velocity of the formation between two boreholes, one of which contains sources(s) and the other detectors(s) and used to determine general rock structure in the panel between two holes

Table B.1 (continued)

Data Determination Method
Structural Framework (continued)
- Fluid Resistivity – measures electrical resistivity (which is related to the dissolved solids concentration) of the water in a borehole; used in conjunction with temperature and flowmeter logs to infer locations of fractures based on flowing water - Temperature – direct measurement of borehole fluid temperature to within 0.001 degrees C; used to detect water movement through and between fractures; provides in situ temperature data needed for diffusion parameter definition at DGR depth - Heat Pulse Flowmeter – measures time required for a temperature pulse to travel from a source to thermistors above and below probe; used to determine low levels of vertical water movement in open boreholes and infer locations of significant fractures or changes in flow conditions - Impeller Flowmeter – measures vertical flow with an impeller; used to identify high levels of vertical water movement in an open borehole and locate significant fractures or changes in flow conditions - EM-Flowmeter – records the direction and rate of vertical flow in a borehole by measuring the voltage gradient generated by the flow of water through an induced magnetic field - Open-hole hydraulic testing involving hydraulic testing with dual (or more) packer tool on work-over rig; successive intervals in borehole can be tested to reliably identify transmissive and permeable structural features of importance to the site characterization effort - Surface seismic surveys where the variations of speed and travel time for reflected sound waves produced at surface by explosives, vibrating plates, and air guns (sleeve guns) measured by surface receivers can indicate changes in rock quality due to structure at a particular depth. Surveys can produce information in 2D (lines) or 3D (grid) and cover a larger area than boreholes; can indicate the level of continuity of larger structural features such as tops of formations, major bedding planes, and faults. These surveys will not detect smaller features such as fractures or joints. They are minimally intrusive but usually require borehole information and borehole vertical seismic profiling to improve interpretation. More steeply dipping structures require interpretation of vertical offsets in sub-horizontal layering. Coverage may be limited by surface infrastructure. - Gravity surveys involving high-resolution airborne or ground measurement of gravity and/or vertical gravity gradient to detect changes in subsurface densities of rock units. These surveys have typically been used to map deep lithologic and structural features and some shallow geological features including ore bodies, kimberlite pipes and geologic structures associated with hydrocarbon accumulations. They may have application in mapping strike-slip dolomotized fault zones in the deeper Ordovician argillaceous limestones, provided the differential gravity signature is strong and overlying Devonian and Silurian bedrock is relatively homogeneous gravimetrically. However both of these conditions are unlikely and therefore gravity surveys are unlikely to be useful for this purpose.
Bedrock Petrography and Mineralogy
- Core logging entailing logging of recovered drill core by on-site geologist for changes in rock type, texture, mineralogic composition, layering, hardness, etc. Allows for visual and physical inspection of rock to determine changes in rock type, texture, hardness, and mineralogy; it is the only tangible evaluation of geological environment without larger excavations - Optical microscopy involving conventional analysis of thin sections using microscope to identify petrography and mineralogy of rock samples - X-ray diffraction mineralogy (XRD) involving laboratory analysis which provides quantitative determination of all rock-forming and clay/phyllosilicate minerals including weight percent, volume percent, grain density. A rock thin section is needed for this analysis. - Scanning electron microscope (SEM) involving laboratory evaluation of porosity, pore connectivity and pore throat size, shape, and roughness by preparing rock core samples and obtaining high-quality black and white photomicrographs at various magnifications - X-ray fluorescence (XRF) involving laboratory analysis of the major elements, including the concentrations and distributions of U, Th, and K. Allows for calculation of ^{4}He and ^{40}Ar production rates and in-situ neutron fluxes for ^{129}I and ^{36}Cl in-growth calculations

Table B.1 (continued)

Data Determination Method

Bedrock Petrography and Mineralogy (continued)

- Borehole geophysical testing involving lowering geophysical tools down borehole after drilling is complete and collecting measurements of rock properties allowing differentiation between varying stratigraphic units. Tools useful for determining bedrock petrography and mineralogy include:
  - Gamma - Records amount of gamma radiation emitted by the rocks surrounding the borehole and infers varying clay content
  - Spectral Gamma – detection of gamma radiation emitted from the formation used to differentiate potassium, uranium and thorium content to infer lithology based on clay mineral content
  - Gamma-Gamma (Density) – measurement of electron density obtained by exposing formation to gamma radiation from a source in the probe and infers lithologic contacts and porosity
  - Neutron (Porosity) – measurement of hydrogen content by exposing formation to neutrons from a source on the probe; infers lithologic contacts, water content and porosity
  - EM-Induction (Resistivity) – records electrical conductivity (resistivity) of the rocks and water surrounding the borehole which are effected by porosity and clay content of rocks and TDS of the water
  - Conductivity – measurement of variations is electromagnetic field induced by a transmitter in the probe; used to infer lithology in terms of electrical conductivity (i.e., water/clay content).
- Photoelectric Effect (Lithodensity) – density logging tool that measures absorption of low-energy gamma rays, and is a sensitive indicator of mineralogy. Particularly useful for identification of dolomitized zones in limestone units.

Table B.2 Geomechanical Setting and Rock Properties

Data Determination Method

Existing Geomechanical Information

- In situ stress database on Canadian Crustal Stresses maintained by the National Earthquake Hazard Program, Geological Survey of Canada, Ottawa.
- Ground stress and geomechanical rock properties including data from OPG/NWMO, K.Y Lo reports/papers and from other engineering projects (i.e., aggregate quarries, tunnel project and other underground openings) completed in formations in southern Ontario (e.g. Goderich Sifto Mine) and northern USA.
- NWMO databases on geomechanical properties and in situ stress measurements to be maintained and updated.

In Situ Stress Regime

- In situ stress measurement techniques conducted in drill holes are potentially useful depending on rock quality encountered. These include but are not limited to:
  - Deep Doorstopper Gauge System (DDGS) developed by AECL is a deep overcoring method that uses a glued borehole bottom-cell; provides 2D stresses in plane perpendicular to borehole axis. Does not require pilot hole to be drilled, therefore advantageous in discing or highly fractured rocks; very short length of overcore required. Effectiveness of glue to adhere stress cell to bottom of borehole in deep boreholes filled with water is questionable; not used below 528 m borehole depth; performed while drilling, therefore slows rate of drilling and creates standby charges for drilling crew
  - In Situ Stress Measurement Tool (IST) developed by Sigra Pty Ltd based in Australia is a borehole deformation gauge that is secured in borehole by spring loaded pins. Provides 2D stress information in plane perpendicular to borehole axis. Similar to USBM borehole deformation gauge. Does not rely on glue to ensure stress gauge is secure; rapid and easy to use, rugged construction; has been used at depths of 750 m below ground surface. Need for fairly long overcore (1 m in length) which creates problems where core discing or highly fractured rocks are encountered; limited data available for comparison to other tests under appropriate quality assurance plans.

Table B.2 (continued)

Data Determination Method

In Situ Stress Regime (continued)

  - Borre Probe (SSPB) is a glued soft cell inclusion method developed in Sweden. Provides 3D stress information; has been used at depths of 600 m below ground surface. Needs a fairly long overcore (50 cm in length) which creates problems where core discing or highly fractured rocks are encountered. Sensitive to grain size variation and rock anisotropy
  - Hydraulic fracturing involves injecting fluid between two straddle packers to a level that causes fracture creation or re-opening of existing fractures. Theoretically new fractures are created at an orientation perpendicular to the minimum principal stress and the stabilized fluid injection pressure required to prop open the fracture is a measure of this stress. Hydrofracturing is a commonly used technique in oil and gas industry and has a long history of use; not limited by depth of application; can be done independently of advancing the drill hole. May create disturbance to groundwater chemistries due to fluid injection; may be difficult to interpret in rock with pre-existing fractures or weakness planes (i.e., horizontal bedding); may only provide vertical stress information in high horizontal stress regimes and horizontally layered rocks typical of the Michigan Basin
  - Sleeve fracturing is a technique similar to hydro-fracturing except the high pressure fluid is contained within a flexible bladder or gland, between the injection packers, and hence the injected fluid does not penetrate the rock mass. Similar advantages to hydro-fracturing; major advantage is that fluid is not injected into the formation. Interpretation of results is often difficult as identification of breakdown and fracture re-opening pressure is difficult to precisely identify; effects of existing fracture/planes of weakness are also difficult to interpret; no substantial precedent experience at the 600 m depth in sedimentary rocks of the Michigan Basin.
- Laboratory core testing involves geomechanical testing of recovered core to determine orientation and magnitude of in-situ stresses (e.g., Kaiser effect testing). Provides 3D state of stress using conventional intact bedrock core, and hence does not interfere with costly additional field drilling and borehole testing methods. Evidence showing comparable results to other accepted test methods (i.e, overcoring), is limited and not compelling.

Rock Material Properties

- Lithologic and petrographic analysis involves standard descriptions and petrographic/ mineralogic analyses of rock materials (see Table B.2 Rock Mass Properties) based on inspection and laboratory testing of recovered core.
- Standard index tests include conventional aggregate industry index tests such asg hardness, density, abrasion resistance, soundness, slake durability; used to assess issues of waste-rock utilization, trafficability and wet/dry degradation. Use of standard aggregate testing methods allows for comparison with regional quarry data.
- Strength and deformation parameters include full stress-strain curves in uniaxial compression along with acoustic emission data, longitudinal, transverse and volumetric strains under both saturated and dry conditions. Data used to evaluate Young's Modulus, Poisson's Ratio, various crack-initiation and crack-propagation parameters, various strength "thresholds" (crack initiation; cohesion loss, stable crack growth; long-term strength; peak strength, etc.). Full suite of triaxial compression testing required to evaluate appropriate strength envelopes for analysis/design purposes (Hoek-Brown, Modified Hoek-Brown, Mohr-Coulomb, etc.). Testing required on rock cores at different orientations with respect to stratigraphy in order to assess anisotropy, using sub-coring from primary core. Sonic velocity (P and S wave) measurements for dynamic modulus should be completed on fresh intact cores, parallel and perpendicular to core axis, and possibly repeated after 1 month to assess deterioration due to weathering. Brazilian tests and direct tensile tests used for tensile strength. Deformation parameters to be determined from biaxial testing of core recovered at each overcoring stress-measurement location.
- Creep parameters determination requires testing in the Lindsay Formation, sufficient to confirm expectation that creep will not be a significant design/performance issue. Creep/accelerated-creep laboratory tests required on rock material from overlying shales. Collect and evaluate existing data from precedent projects in these units prior to site-specific tests.
- Swelling/squeezing tests are not anticipated in the Lindsay Formation, but require limited testing to confirm. Laboratory testing will be required on rock materials from overlying shale formations, to identify/assess shaft stability/support issues. Collect and evaluate existing data from precedent projects in these units prior to site-specific tests.
- Thermal properties determination requires limited testing for coefficient of linear expansion, thermal conductivity and thermal diffusivity of rock from each formation.

Table B.2 (continued)

Data Determination Method

Rock Mass Properties

- Borehole core logging involving continuous collection of rock core while drilling; to be logged immediately by on-site geologist for bedding plane contacts between different layers and structural features such as faults, fractures zones, smaller fractures or joints as well evidence of weathering or chemical alteration, rock quality designation (RQD) and evidence of core discing
- Borehole geophysical surveys involving lowering geophysical tools down borehole after drilling is complete and collecting measurements of rock mass properties. The following borehole geophysical logs are useful for defining rock mass properties for geomechanical purposes:
  - Acoustic Televiewer – highly detailed measurement of borehole diameter obtained by timing the return reflection of an acoustic pulse of the borehole wall back to the probe; primarily used to infer fractures and there orientation, borehole diameter and borehole orientation. Successive logging can identify borehole deformation due to creep and borehole breakouts due to high rock stress
  - Optical Televiewer – collects an oriented image of the borehole wall which undergoes “restoration” to correct for optical distortion and creates a “virtual core”; primarily used to indicate fracture location but also provides some lithologic information
  - Acoustic Velocity – measurement of the velocity of acoustic energy (seismic waves produced by a downhole sonde) in the material adjacent to the borehole; used to infer lithology variations and fracture locations
  - Caliper – mechanical measurement of borehole diameter based on the extension of 3 or 4 caliper arms. Similar application to acoustic televiewer re mapping creep and stress breakouts.
  - Borehole-Radar Reflection – records the reflected wave amplitude and transit time of high-frequency EM waves using a pair of downhole transmitting and receiving antennae; used to determine the location and dip of fractures and lithologic changes and to estimate the radial extent of such features beyond the borehole (3 to 10 m radial penetration dependent on the electrical resistivity of the rock and water surrounding the borehole)
  - Full Waveform Seismics – measurement of the compressional (P), shear (S) and Stoneley seismic velocities using a probe source(s) and detectors (transducers); useful for estimation of Poisson’s ratio and Young’s shear and bulk modulus.
  - Vertical Seismic Profiling – measurement of shear and compressional seismic velocities using a surface source and borehole detectors (geophones) to calculate bulk modulus and infer general rock competence and lithology.
  - Cross Hole Seismic Profiling (Tomographic Survey) – measurement of shear and compressional seismic velocity of the formation between two boreholes, one of which contains sources(s) and the other detectors(s); used to determine general rock competence (calculates bulk modulus).
- Open-hole hydraulic testing involves dual (or more) packer tool on work-over rig, successive intervals tested. Provides integrated measure of bulk rock hydraulic conductivity and hence assessment of likelihood of fracturing.
- Laboratory testing of rock material properties including testing for shear strength parameters of bedding plane features within DGR horizon to provide needed data for design considerations

Table B.3 Hydraulic Properties and State

Data Determination Method

Existing Hydrogeological Information

- Municipal Groundwater Study, Bruce & Grey Counties describes mapping and assessment of groundwater resources (quantity and quality) in Grey and Bruce Counties as part of Ministry of Environment-sponsored municipal groundwater studies. Identifies, characterizes and maps groundwater sources of drinking water in Bruce County based on MOE water well records, and available overburden and bedrock geology mapping. Similar studies available for other areas.

Table B.3 (continued)

Data Determination Method
Existing Hydrogeological Information (continued)
- Hydraulic information from studies including results of laboratory testing and deep borehole hydraulic testing programs and hydraulic head monitoring in Westbay completions undertaken in bedrock formations in Ontario and the Michigan Basin as part of other studies (i.e., UN-2 at Darlington, OHD-1 at Lakeview, MDMW-1 at Sarnia, Niagara Falls). Also inflow data from excavations and tunnels in select bedrock formations. - Hydrogeologic information from studies including results of borehole drilling, hydraulic testing and monitoring completed in the overburden and shallow bedrock at the Bruce site. For example water level and hydraulic conductivity data collected from OPG intermediate depth bedrock monitoring wells US-1, US-5, US-6 and US-7 (Westbay MP completions) and US-3 and US-4 (open boreholes), including 1995 work described in AECL Report COG-95-248.
Rock Mass Hydraulic Conductivity
- Single-packer bottom-hole testing invovles hydraulic testing concurrent with drilling through the drill stem (through-the-bit) or after drill string withdrawal and insertion of a single packer on tubing. Minimizes effect of borehole history, simplifies analyses; provides information quickly. Disrupts drilling; testing decision must be made with no knowledge of what lies deeper (that may be of more interest); presence of drilling fluid complicates testing and analyses; no opportunity to develop well (reduce skin effects) - Open-hole straddle packer testing involves hydraulic testing with dual (or more) packer tool on work-over rig, successive intervals tested. Can perform slug, DST, and/or pulse tests. Can preferentially test zones of interest identified from core examination and borehole geophysical logging; drilling fluid can be purged. Borehole history effects necessitate longer recovery/stabilization times to estimate hydraulic head; multiple intervals are left commingled for some period of time, leading to mixing of fluids; borehole stability can be an issue - Testing in multi-level monitoring casings (i.e., Westbay) invovles testing in predefined isolated intervals. Convenient, limited equipment required. Intervals must be selected prior to casing installation – no possibility of modification after; compliance effects more severe, reliance on multi-level seals (i.e., packers); testing options (types) limited - Pumping tests involve pumping from isolated interval using bridge plugs and packers. Provides properties representative of greater volume of rock than other methods; standard equipment required; single fluid (formation water) in both borehole and formation; can estimate storativity if observation well(s) nearby. In well open to multiple intervals, multiple trips in and out of hole required to set bridge plugs, pump and packer; not practical in low-permeability media; water disposal can be an issue; hole stability can be an issue - Laboratory core permeability tests involve laboratory testing of intact rock core for hydraulic conductivity under confining pressure using constant head flow tests or pressure transient pulse testing. Can provide estimates of anisotropy in hydraulic properties of intact rock under controlled laboratory conditions; provides a matrix permeability for comparison to in situ field tests (assists in defining field tests that may exhibit effects of fractures). Unloading of rock cores can induce micro-fracturing, that may be irreversible and hence overestimate permeability; testing should be done with representative pore water chemistry
Hydraulic Heads
- Electromagnetic Pressure Gauge (EPG) sensors are dedicated wireless pressure sensors that measures hydraulic pressures in low permeability environments; sealed in a borehole using a dedicated packer system and low permeability cement plug. Developed and used successfully as part of the ANDRA Program. Equilibrium pressure in very low permeability environments is quickly achieved (within 6-12 months); no concern over effective seals of packers on the borehole walls; demonstrated to provide the highest quality estimate of static (undisturbed) formation pressure in very low permeability formations. Prevents further monitoring in the section of borehole where the sensor and low cement are installed; battery life is approximately 3 to 5 years; cannot remove sensor to recalibrate or move to another location; sensor must be within 70 m of steel casing, therefore preventing dual use of Westbay casings and EPGs in same hole

Table B.3 (continued)

Data Determination Method
Hydraulic Heads (continued)
- Pressure monitoring in multi-level Westbay casings involves pressure sensor(s) lowered at a selection of monitoring intervals within a multi-level system (such as the Westbay MP system) to collect continuous or point data over time in order to evaluate transient and static hydraulic heads within all of the bedrock units. Commercially available; pressure transducers can be removed and recalibrated or redistributed to other intervals; allows for vertical interference testing and reliable long-term pressure monitoring. Pressures within a multi-level packer system may take a longer time to equilibrate than cemented in pressure gauges isolated with packer and cement plug (i.e., EPG completion); borehole conditions must be good to provide an effective seal between packers and borehole walls - Pressure or level monitoring in multi-packer standpipe completions involves surface monitoring of water levels (via dedicated standpipes or tubing) or pressures (via signals from dedicated pressure transducers) in intervals created by a series of inflatable packers with feed-through assemblies. Packer pressures can be monitored if inflation lines extend to surface providing confidence in borehole interval seals; allows for vertical interference testing and reliable long-term pressure monitoring. Requires larger diameter boreholes; number of intervals is limited by borehole diameter, typically limited to maximum of 4 to 6 intervals per borehole; density profile of water column in standpipe or tubing is required to convert water levels to hydraulic heads
Total and Effective Rock Matrix Porosities
- Conventional oven drying method where total or ‘water-content’ porosity is determined from the difference in weight between an oven-dried and water-saturated rock specimen. Low cost. From experience at Mont Terri, method likely to overestimate both solute diffusion and geochemical porosities (see Pearson, 1999, What is the porosity of a mudrock?) - Mercury-injection porosimetry methods are based on the intrusion of mercury into a porous structure under stringently controlled pressures. Since mercury does not wet most substances and will not spontaneously penetrate pores by capillary action, it must be forced into the pores by the application of external pressure. The required pressure is inversely proportional to the size of the pores, only slight pressure being required to intrude mercury into large macropores, whereas much greater pressures are required to force mercury into micropores. With accurate pressure measurements, the resulting pore size data is very accurate. Measures the pore size distribution and allows estimation of the capillary pressure curve and ultimately enables the N_2/brine relative permeability curves to be developed. This is a destructive technique, therefore further testing on sample specimen is not permitted. Proven method for measuring pore-throat sizes and variability. Very long injection periods must be anticipated in order to allow Hg to penetrate to relatively high saturations and therefore measure a significant number of pore throats; tests may not access smaller pores; concern expressed by Horseman of BGS that Hg injection causes damage to small pores. - Gas expansion and Boyle’s Law method involves filling the pores of a rock core sample with an ideal gas such as He, and measuring the pressure of the gas, from which the volume (therefore porosity) can be measured by applying Boyle’s Law. - Diffusion-cell testing whereby an estimate of the effective or solute diffusion porosity is obtained from through-diffusion or out-diffusion tests in the laboratory. Tests likely to give a meaningful estimate of porosity for diffusion and geochemical modeling. Relatively expensive - H_2O and N_2 – adsorption – desorption isotherm method involves measurement of H_2O and N_2 – adsorption – desorption isotherm which is used to estimate physical porosity
Fracture/Fault Hydraulic Properties
- Single-packer bottom- hole testing - see discussion in Table B.3 Rock Mass Hydraulic Conductivity - Open-hole straddle packer testing - see discussion in Table B.3 Rock Mass Hydraulic Conductivity - Testing in multi-level monitoring casings (i.e., Westbay) discussion in Table B.3 Rock Mass Hydraulic Conductivity - Pumping tests – see discussion in Table B.3 Rock Mass Hydraulic Conductivity - FLUTe™ Hydraulic Conductivity (FHC) profiler involves measuring and electronically recording the rate of descent while installing a blank FLUTe™ liner which can then be used to calculate the rate at which water is displaced into the rock formation. Provides continuous hydraulic conductivity profile in a section of borehole that can then be tested more precisely using conventional straddle packer testing equipment. Not effective in low permeability environments; borehole water is displaced into the rock fractures/matrix, therefore chemical alteration may be a concern

Table B.3 (continued)

Data Determination Method
Gas–Brine Flow Properties
- In-situ gas-entry tests below or between packers, replacing drilling fluid with gas while maintaining constant pressure, then increase gas pressure until pressure rise deviates from unit-slope line, indicating end of wellbore storage period and gas entry into formation. Provides measurement of gas-entry pressure. Possible borehole skin and fluid incompatibilities may lead to questionable data - Laboratory petrophysical testing involves single phase flow tests (absolute permeability) followed by gas breakthrough testing on core samples. Standard techniques used in oilfield analyses. Widely available, well understood tests for porosity and permeability. Laboratories may not be equipped to perform tests on very low permeability materials.
Groundwater Densities
- Laboratory analysis of groundwater/porewater involving measured fluid weight or calculated from measured total dissolved solids.

Table B.4 Diffusion and Sorption Properties

Data Determination Method
Effective Diffusion Coefficients and Effective Diffusion Porosities
- Free-water diffusion coefficients are available in the literature at selected temperatures and in dilute aqueous solutions. Values at other temperatures and in saline solutions can be calculated using relationship principally dependent on water viscosity. - “In Diffusion” laboratory tests allow the radionuclide to diffuse from a central reservoir or well into the core “doughnut” surrounding it. After a certain time the experiment is ended and the diffusion profile in the core is measured. This technique is used for more strongly sorbing radionuclides. Combined with information of the concentration evolution in the reservoir, both the effective diffusion coefficient and the rock capacity factor can be derived for the radionuclide employed. Without the reservoir information, only an apparent diffusion coefficient can be extracted from the profile. Suitable for strongly sorbing radionuclides, e.g., ^{60}Co, ^{90}Sr and other hydrolysable cations. Long experimental times required, e.g., one year. Small core sample size may be a disadvantage if sample is smaller than representative elementary volume (REV). - “Through-Diffusion” laboratory tests whereby a section of core is cut in cross section to produce a rock wafer which is then placed in a diffusion cell with two reservoirs on either end, each maintained at the same pressure. One reservoir is filled with a known concentration tracer solution and the other reservoir is filled with a fluid of similar ionic strength but lacking the tracer. The concentrations in both reservoirs are measured over time and the rate of diffusion is measured. This method provides an effective diffusion coefficient and effective diffusion porosity as well as the retardation factors for weakly-sorbing radionuclides. Suitable for weakly sorbing radionuclides, e.g., I, Cl and Tc and other anions. Small core sample size may be a disadvantage if sample is smaller than representative elementary volume (REV). - In situ diffusion tests developed at ANDRA’s Bure site in France. Using deep drilling methods from ground surface, a pilot hole is drilled at the bottom of the borehole into which a radial diffusion experiment is performed (in the intact rock). After a sufficient time has elapsed, the reservoir is overcored and the resulting rock specimen is sampled and the diffusion profile measured. Combined with information of the concentration evolution in the reservoir, both the effective diffusion coefficient and the rock capacity factor can be derived for the radionuclide employed. Without the reservoir information, only an apparent diffusion coefficient can be extracted from the profile. In situ measurements are performed under more representative stress and chemical conditions; encouraging results from Mont Terri and ANDRA experiments. High cost and potential interference by drilling. Although theory is well established, methods for conducting tests at large borehole depth need standardization and international acceptance. Does not necessarily provide a better estimate than laboratory values.

Table B.4 (continued)

Data Determination Method
Effective Diffusion Coefficients and Effective Diffusion Porosities (continued)
- Laboratory formation factor whereby electrical resistivity measurements are performed in the laboratory on core plugs. The constant of proportionality relating the resistivity of the core plug and its saturating fluid is called formation factor (>=1). Performed after matrix porosity determination. Matrix tortuosity can be calculated as the reciprocal of the product of formation factor and matrix porosity. The effective diffusion coefficient of the solute in the matrix can be calculated as the product of tortuosity and solute free-water diffusion coefficient. The advantage of this method is that formation factor determinations are inexpensive allowing determination of diffusion properties at multiple locations and lithologies at relatively low cost. The correlations between electrical resistivity and tortuosity are not well established, and hence the estimates of effective diffusion coefficients are only approximate.
Sorption Parameters
- Laboratory batch tests involve adding a known amount of solute to a known amount of rock and allowing concentration to come to equilibrium. Measuring the equilibrium concentration will allow determination of amount of solute sorbed onto rock. Varying the initial concentration will allow a plot of equilibrium concentration vs. mass adsorbed which can be fit to a model to determine Kd and allow any concentration dependence to be determined. These results can be compared with diffusion testing results. Obtains first approximations of radionuclide retention that will allow comparison with Kd values from retardation factors. Requires robust conceptual model of pore-water geochemistry that will allow appropriate experiments to be conducted with specified amounts of sorbent of specified surface area and specified anion competitors. - Accelerator Mass Spectrometry (AMS) is an ultra-sensitive technique for measuring isotopic ratios of the abundant to rare isotopes of beryllium, carbon, aluminum, chlorine, iodine etc. For specific sites, the concentration of ^{129}I and ^{36}Cl in different solid phases is essential for characterizing radioiodine and radiochlorine partitioning, for assessing anion ages for these fluids in the Ordovician shale and limestone, and for assessing the mobility of these radionuclides in the geosphere. Allows the use of a smaller sample, provides faster analysis times and greater sensitivity than other mass spectrometry or decay counting techniques. Furthermore, extraction of the sorbed and crystallographic fractions by pyrolosis of the solid phases is essential to establish the immobile phase of these radionuclides. Proposed to be conducted on a relatively small number of samples (each sample requires 1-10 mg of iodine or chlorine). Extreme sensitivity for ^{129}I and ^{36}Cl. Mass required may be limiting in some cases - Organic carbon determination involves measuring the amount of organic matter in a rock sample which is analysed for total kerogen and bitumen and for their elemental compositions in terms of C, O, N, S, and H. - Cation Exchange Capacity (CEC) determination measures the ability of the rock to adsorb and exchange cations and therefore provides an indication of how much potential there is for sorption of cations. Important for reconstructing geochemical model of groundwater evolution; also provides cation occupancy data, i.e., exchangeable cations. - Adsorption isotherms includes measurement of ion-exchange isotherms involving H+ exchange with major cations. Preferred over measurement of selectivity coefficients. Important for reconstructing porewater chemistries from limited porewater characterization data and in part will contribute to determination of sorption parameters.

Table B.5 Groundwater/Porewater Characterization

Data Determination Method
Existing Hydrogeochemical Information
- Municipal Groundwater Study, Bruce & Grey Counties describes mapping and assessment of groundwater resources (quality) in Grey and Bruce Counties as part of Ministry of Environment-sponsored municipal groundwater studies. Identifies, characterizes and maps groundwater quality in Bruce County based on MOE water well records, and available overburden and bedrock geology mapping

Table B.5 (continued)

Data Determination Method
Existing Hydrogeochemical Information (continued)
- Hydrogeochemical information from other studies includes results of groundwater sampling and laboratory analytical testing of deep boreholes and monitoring in Westbay completions undertaken in bedrock formations in Ontario and the Michigan Basin as part of specific studies (i.e., UN-2 at Darlington, OHD-1 at Lakeview, MDMW-1 at Sarnia, Niagara Falls). Covrers results of groundwater sampling and laboratory analytical testing of monitoring wells completed in the overburden and shallow bedrock at the Bruce site. For example, hydrogeochemcial and isotopic data collected from OPG intermediate depth bedrock monitoring wells US-1, US-5, US-6 and US-7 (Westbay MP completions), including 1995 work described in AECL Report COG-95-248.
Major Ion, Trace Element and Isotope Chemistry
- Groundwater sampling during drilling involves collecting groundwater samples during the drilling process by stopping drilling and pumping from drill rods via submersible pumps, with or without single packers installed through the drill bit or on the bottom of the drill rods. This method of groundwater sampling is preferred for the Silurian and Devonian bedrock where the higher bedrock permeabilities will allow recovery of drill fluids from permeable horizons or zones of lost or reduced drill fluid circulation. Such opportunistic sampling may provide the best chance of obtaining representative groundwater samples from the deeper parts of the Devonian and Silurian bedrock that may have lower hydraulic heads and hence may be subject to extensive drill fluid and cross-formational fluid contamination during drilling and while the hole stays open. - Temporary borehole sealing using bridge plugs or PIPs whereby bridge plugs or production-injection packers (PIPs) can be remotely set at different depths in a borehole to prevent the cross connection of fluids (leading to cross contamination of formation waters) after a section of borehole is completed drilling. Bridge plugs and PIPs provide excellent seals and can seal against high pressure or gas producing zones - Tracers for drilling operations involves adding a Na Fluorescein solution to all drilling fluids to allow rapid laboratory and field identification of drill fluid contamination of rock samples from which the pore-water is to be extracted and of groundwater samples to be collected from Westbay multilevel installations or during pumping tests of open boreholes during drilling. Other fluorescent dyes may also be used as drill water tracers. As a potential source of drilling fluid, parts of Lake Huron have elevated tritium concentration, therefore tritium can also be used as a drill water tracer in some cases. Special care will need to be taken to ensure that deep groundwater samples are not contaminated with atmospheric tritium. Tritium requires laboratory analysis of drill water samples to determine potential drill water contamination levels. - Groundwater sampling from multi-level system involves collecting groundwater samples from depth over discrete monitoring intervals pre-determined by the configuration of the multilevel monitoring system (i.e., Westbay system). Sampling tool is lowered to selected port and attached to sampling valve which allows groundwater to flow into a sealed sampling container that is raised to surface for analyses (water flows based on pressure difference between sample container and formation). Samples can be collected at in situ pressures, therefore minimizing de-gassing and subsequent changes in chemistry. Water between Westbay casing and the borehole wall must be purged prior to sample collection; therefore low permeability borehole intervals will present problems for sample collection. - Preservation of rock cores (Teflon-lined bags flushed with N_2 gas). Rock cores are preserved in Teflon-lined aluminized bags that are then flushed with N_2 gas, vacuum-extracted, and then heat sealed in the field. Minimizes oxidation of analytes. Potential for loss of dissolved gases. - Preservation of rock cores (wrapping with plastic, aluminum foil and wax). Rock cores are preserved by immediately wrapping a section in two layers of plastic wrap, followed by two layers of aluminum foil followed by a 1-cm thick layer of wax. Minimizes loss of dissolved gases, oxidation of analytes, evaporation of pore fluids. Labour intensive, potential loss of seal over long-term (> several months) - Preservation of rock cores in sealed cylinders. Rock cores are preserved by placing in sealed cylinder, flushing the cylinder with nitrogen or argon gas, imposing a minor pressure differential on the cylinder to allow detection of any cylinder leakage. Very effective in reducing long-term (> several months) loss of dissolved gases, oxidation of analytes, evaporation of pore fluids. Labour intensive.

Table B.5 (continued)

Data Determination Method
Major Ion, Trace Element and Isotope Chemistry
- Pore-fluid extraction by centrifuge extraction whereby core sections are centrifuged to allow drainage of porewaters or their displacement with CFC113 or other suitable inert, dense liquid. Rock is required to have water content > 4% and well-interconnected porosity (i.e., high effective porosity), otherwise it will be necessary to crush the rock first. Provides a high quality water sample that is both representative of the chemical and isotopic composition of the in-situ porewater. 25 years of experience in UK sedimentary rocks with this technique; drainage centrifugation is non-destructive and would allow core samples to be used for additional testing. Labor intensive; the method will not be suitable for highly indurated or low moisture content samples; control of redox conditions is more difficult compared to mechanical porewater squeezing and crushing/leaching techniques; requires well interconnected porosity to work without crushing; displacement centrifugation is destructive.
- Pore-fluid extraction by crushing core and aqueous leaching whereby crushed core material is centrifuged in the presence of de-ionized water, filtered then preserved for analysis. In cases in which the rock is of low porosity and strongly lithified, this may be the only approach possible to extract porewaters. If there are a series of samples taken from contiguous depths ranges (i.e., >10 m) then data processing techniques are available to allow rock water interactions to be removed and good estimates of the major ion chemistry can be obtained (Na, K, Ca, Mg, HCO_3 -, Cl, SO_4) with possibilities of mapping down hole porewater concentration profiles. In the worst case a good estimate of the chloride content of the porewater will be obtained. Rock-water interactions – dissolution of fresh mineral surfaces, dissolution of fluid inclusions – can make the data difficult to interpret; information on the stable isotopic composition of the porewater will not be able to be measured; relies on crushing of core, therefore a destructive technique that does not allow further testing of specimen.
- Pore-fluid extraction by high-pressure squeezing. For argillaceous material with a moisture content > 4% and not excessively stiff, porewater can be obtained from the rock core sample by squeezing the core in a mechanical squeezing rig for between approximately 7 and 21 days, until sufficient porewater is collected to enable full chemical characterization. The extracted porewater may either be treated as a single bulk sample, or, assuming sufficient sample can be collected from each core, as a series of sequential fractions which may be used to study porewater fractionation. If the core material is redox sensitive (presence of pyrite), it will be necessary to use a specially designed nitrogen-filled chamber. If moisture content < 4%, re-hydrating the core material (clay) with deionised water and then squeezing the resulting mixture has been shown to provide estimates for the true in-situ composition however information on trace elements and isotopic composition was not obtained. Where the moisture content is very low, this may be the best method of obtaining a representative sample of in situ porewater and being able to determine the stable oxygen and hydrogen isotopic data. A new high duty squeezing cell is available at BGS. This heavy duty squeezer has a similar design to the standard system but will provide squeezing pressures up to 350 MPa, more than three times as much as the standard system allowing the extraction of pore-waters from very low moisture content (3-4 %) samples although this will be dependant on the their mineralogy and structure. The method may not be able to extract porewater from highly indurated or low moisture content samples.
- Diffusive exchange is based upon the van der Kamp method for clay tills. A test water of known isotopic ($\delta^{18}O$ and $\delta^{2}H$) concentration is brought into contact with a small quantities of rock in a water-tight tin-plate container and allowed to equilibrate. After 10-20 days the test water is analyzed and the change in $\delta^{18}O$ and $\delta^{2}H$ reported. Provides a good estimate of stable O and H isotopes within 10-20 days. May require some correction for $\delta^{2}H$ due to the addition of NaCl to minimize vapor loss and isotope fractionation
- High-pressure fluid displacement involves using triaxial confining cell, in which an immiscible liquid like CFC-113, other suitable inert, dense liquid, or tracer-tagged synthetic pore-water is driven through the rock sample and collected in the reservoir beneath. By using an inert dense liquid it may be able to minimize dissolution of minerals during extraction. Displacing liquid can be toxic and the core cannot be used for additional testing.

Table B.5 (continued)

Data Determination Method
Dissolved Gases
- Downhole sampling using pressurized copper tubing whereby 9.4 mm (3/8”) polyethylene tubing with a 1.3 m long 9.4 mm (3/8”) OD copper tube fitted with a check valve is lowered into the borehole to the desired depth and pressurized using a hand pump or a compressor. The sample is raised to surface and the copper tube is clamped at each end and transported to the laboratory for analysis. Offers easy operation; sample can be collected in an open borehole or in a Westbay casing; proven techniques by AECL and INTERA. Lowering equipment with clamped joints into the borehole/multilevel system has opportunity to disconnect; allowing formation water to enter into Westbay casing will “cross contaminate” over the length of the casing and therefore could pose an issue for future sampling from other zones - Groundwater sampling during drilling and from Westbay system - see Table B.5 (Major Ion, Trace Element and Isotope Chemistry) - Extraction of dissolved gases in porewater by sequential heating (vacuum/azeotropic distillation) whereby a sub-sample of core is sealed within a stainless steel high-vacuum container that is evacuated to 10-5 torr and 25˚C and then heated sequentially from 30 to 500˚C with the concentration of helium extracted measured at each heating step. Procedure previously successful on clay rich aquitards from Saskatchewan for He, Ne, Ar, and N_2
Redox States
- Measurement of redox conditions involving measurements of Pt electrode potential (Eh), methane and hydrogen sulphide gases, identification of sulphide minerals and sedimentary organic carbon will be used to define the redox environment present within the porewaters. Simple and inexpensive means of characterizing the general redox environment. Not amenable to quantitative definition of redox potential because of lack of sufficient quantities of electroactive pairs - X-ray Absorption Near Edge Spectroscopy (XANES). Using the Canadian Light Source in Saskatoon, this technique will allow the determination of formal oxidation states and complexes of many elements, in particular I and Cl. It is proposed to use the XANES spectroscopic technique on well characterized rock samples containing sufficient quantities of I or Cl (tens of ppm) to obtain information regarding the formal oxidation states of these anions and associated complexes. The capability to conduct these measurements on rock samples is valuable since both the oxidation state and species of iodine can directly affect the degree to which iodine is sorbed to mineral and organic surfaces and thus retarded, thereby influencing the “conservative” nature of dissolved iodide (I-) or iodate (IO_3 -) in groundwater systems. Innovative technique and therefore subject to peer-review critique
Water Physical Properties

- Borehole geophysical testing (porosity, salinity) using the following methods
  - EM-Induction (Resistivity) – records the electrical conductivity (resistivity) of the rocks and water surrounding the borehole which are effected by salinity of the water; helps to estimate sorption parameters
  - Fluid Resistivity – measures the electrical resistivity (which is related to the dissolved solids concentration, therefore salinity) of the water in a borehole; helps to estimate sorption parameters
  - Temperature – direct measurement of borehole fluid temperature to within 0.001˚C which helps to estimate advection and diffusion rates
- Downhole measurements in Westbay system invovles measurement of in-situ temperature and pressure at time of groundwater sampling using the sampling probe provided with Westbay system
- Laboratory analysis on groundwater/porewater samples includes measurements of fluid density (comparing to unit weight of pure distilled water) and dynamic viscosity (measuring time for a known volume of fluid to flow through a known diameter capillary tube). Calculations of density from major ion analyses.

Table B.6 Seismicity

Data Determination Method
Map Significant Local Faults
- See Table B.1 (Structural Framework)
Local Seismographic Monitoring
- Add new seismographic stations within 50 km of site. POLARIS type (www.polarisnet.ca) stations in use in Southern Ontario would be ideal for this purpose, and could be sited at locations having AC power and communications (internet) to reduce costs.