

Reasoned Argument Why Large-Scale Fracturing Will Not Be Induced by a Deep Geological Repository

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ABSTRACT: This paper outlines a reasoned argument why no large-scale fracturing or faulting will be induced in the host rock by a deep geological repository (DGR) for nuclear fuel waste. Four DGR designs in three possible host rocks, including crystalline and sedimentary rock types, are considered. The reasoned argument draws from results of previously conducted thermal-mechanical analyses and new scoping calculations, along with evidence from experiments conducted in Canada and elsewhere. It is concluded that large-scale fracturing in the far-field is implausible given the expected in situ stress conditions in relation to rock strength. Near-field damage development and fracturing are expected in DGR scenarios in the different rock types, but these near-field effects are not expected to lead to large-scale fracturing that could compromise the integrity of the DGR and surrounding rock mass. Additional analysis and characterization activities are recommended to further validate the reasoned argument. Thermo-poroelastic loading of the rock mass is identified as one possible driving mechanism that should be studied further.

1 INTRODUCTION

The Canadian approach for long-term containment and isolation of spent nuclear fuel (termed 'used fuel') in a deep geological repository (DGR) relies on multiple barriers to prevent or retard the release of radionuclides to the biosphere. The system includes the host rock (or geosphere) as a natural barrier, and a series of engineered barriers placed in underground excavations in the host rock. Both crystalline rock and sedimentary rock are considered potentially suitable host rock formations (NWMO 2005). These formations exhibit desirable mechanical and hydrological properties. They also cover large areas at sufficient depth below surface, and are not considered rich in mineral resources, thus limiting the potential for disturbance by erosion or accidental interception during drilling.

For the purposes of safety assessment of a DGR, the integrity of the natural barrier is assumed to remain substantially unchanged over the 100,000 year period following waste placement (i.e. the period in which release of radionuclides to the biosphere would constitute a possible safety risk). Over this time period, the host rock will experience mechanical effects from excavation and development of underground openings, thermal-mechanical effects from heat generated by the placed waste, and possible long-term mechanical effects associated with glaciation and seismicity.

This paper describes a Reasoned Argument (RA) with respect to the likelihood of fracturing and/or faulting of the host rock in response to DGR development and subsequent underground placement of used fuel. The RA considers a number of possible scenarios for induced fracturing of the rock mass in response to DGR development. The RA incorporates observational and experimental evidence from the Canadian and other national radioactive waste management programs, and information from literature related to rock mechanics, geology and seismology.

2 TERMS OF REFERENCE

2.1 *Assumptions and definitions*

The terms of reference for this study (Read 2008) include the following:

- The DGR is constructed in either crystalline rock, typified, for example, by sparsely fractured Lac du Bonnet granite of the Canadian Shield, or by sedimentary rock, typified, for example, by the Ordovician sedimentary rock of the Michigan basin in Ontario (including both shale and limestone).
- Waste placement options considered include the Canadian in-room (AECL-type) option, the in-floor borehole (KBS-3V-type) option, the horizontal borehole (KBS-3H-type) option, and a NAGRA-type option involving placement in long horizontal cylindrical tunnels.
- Repository depths considered for the analysis are 500 and 1000 m for crystalline rock, 500 m for shale, and 750 m for limestone.
- Relevant near-term processes or events include the construction, operation, and backfilling of underground openings in the host rock.
- Relevant intermediate-term processes or events include temperature changes due to the heat-generating used fuel and prolonged monitoring for up to 300 years, during which time the shaft and access tunnels would remain open for possible waste retrieval.
- Relevant long-term processes or events include temperature changes associated with the repository (with placed containers reaching a maximum temperature of 100°C), and geological processes or events such as glaciation and seismicity.

The potential for both vertical and horizontal fracturing/faulting of the host rock, including fracture propagation between sedimentary rock layers, is considered in this context. Large-scale fracturing is defined in this study as the development of new fractures or remobilization of existing fractures longer than 10 m. It should be noted that an explicit analysis of the effects of thermally-induced pore pressure was outside the scope of this study.

2.2 *Synopsis of the Reasoned Argument*

The Reasoned Argument presented in this study can be summarized as follows:

“The development and propagation of large-scale fractures either between repository rooms, or between the repository level and other remote natural hydraulic pathways, is improbable in the various DGR designs in each of the rock types considered. The rock properties in each case are sufficiently competent and stress conditions sufficiently benign to effectively impede the possible fracturing mechanisms discussed in this study. Specifically, the fact that the repository lies in a compressive stress field with relatively low deviatoric stresses in a thrust fault regime suggests that insufficient driving force would exist to initiate and propagate the two types of possible fractures of concern (large-scale horizontal extensile fractures, or thrust faults oriented at a shallow angle to horizontal) within the 100,000 year period following placement. A dramatic erosional event that might reduce the depth of cover by hundreds of metres could alter this conclusion, but the likelihood of such an event over the 100,000 years following placement is considered extremely remote.”

3 DEEP GEOLOGICAL REPOSITORY SCENARIOS

3.1 *Conceptual designs*

The original concept for disposal of Canada’s used fuel (AECL 1994) involved a DGR at 500 to 1000 m depth in crystalline rock of the Canadian Shield. The DGR included up to 512 placement rooms connected by access tunnels and shafts to surface, covering an area approximately 2 km by 2 km. The design was based on vertical placement of used-fuel containers (UFCs) in augered cavities in clay-based buffer compacted in large-diameter boreholes in the floor of placement rooms (Simmons and Baumgartner 1994). Placement rooms (Figure 1a) in this design are backfilled with a mixture of clay and crushed rock materials, and sealed with a concrete bulkhead at the room entrance. This design was based on an inventory of 10.1 million used fuel bundles placed in approximately 140,000 titanium containers.

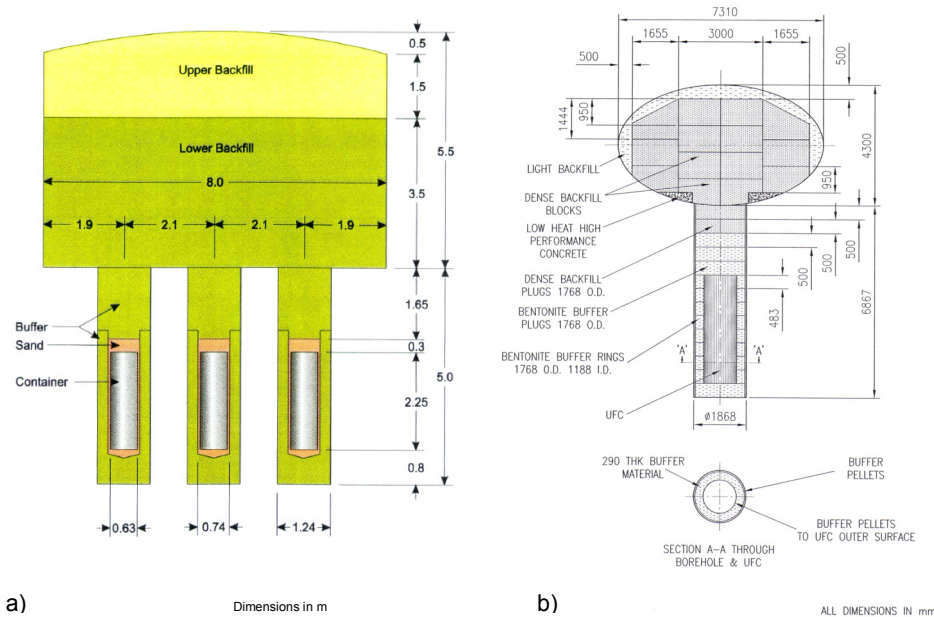


Figure 1. In-floor borehole placement concepts: a) original AECL design (AECL 1994), and b) modified design (RWE-NUKEM 2003) based on the KBS-3V concept.

An alternative placement design developed by AECL (Baumgartner et al. 1996) incorporated in-room placement of used fuel in shorter, larger-diameter copper containers. The UFCs in this design were placed horizontally within cylindrical cavities in pre-compacted clay-based buffer blocks surrounded by backfill materials filling the placement room. This arrangement eliminated the need for large vertical placement boreholes. Each placement room has a concrete floor, and is sealed with a concrete bulkhead. Based on 512 placement rooms covering a 2 km by 2 km area, the capacity of this alternative design was 5.8 million used fuel bundles placed in 80,707 containers.

Four other conceptual DGR designs considered for possible application in Canada include: (1) a modified in-room placement design based on the original AECL design, (2) a modified in-floor borehole placement design based on the Swedish KBS-3V concept, (3) a modified in-borehole placement design using long horizontal boreholes to place UFCs based on the Swedish KBS-3H design, and (4) a modified in-room placement design using long horizontal cylindrical tunnels to place UFCs based on the NAGRA disposal concept. These designs were used for the study, and are described by Read (2008) along with associated references.

3.2 Crystalline host rock

To assess feasibility of the various DGR concepts, the host rock in base case scenarios was assumed to be sparsely fractured crystalline rock of the Canadian Shield. The properties and in situ conditions of the rock mass are based largely on studies conducted by AECL in the Lac du Bonnet batholith at the Underground Research Laboratory (URL) near Lac du Bonnet, Manitoba, Canada. This particular site was selected for the study because the rock mass at the site has been investigated more thoroughly than any other crystalline rock mass in Canada, and large-scale fracturing scenarios are more conceivable at this site due to high stress conditions, isolated fracture zones, and otherwise intact rock.

The Lac du Bonnet batholith comprises a relatively undifferentiated massive porphyritic granite-granodiorite. Textural and compositional layering is evident in the URL shaft, where it has been shown to influence localization of low-dip thrust faulting, and the frequency and properties of subvertical fractures. These variations in lithology and rock fabric have been shown to influence the nature and character of excavation-induced damage around underground excavations (Read & Martin 1996, Read 2004, Everitt & Lajtai 2004). Several major low-dipping thrust

faults (referred to as Fracture Zones) exist near the URL. The most prominent of these thrust faults, Fracture Zone 2, intersects the URL shaft at a depth of about 270 m below surface.

3.3 *Sedimentary host rock*

For the purposes of this study, a simplified lithostratigraphic section was developed based on generic sedimentary southern Ontario conditions. A reddish-brown shale (mudstone) with occasional interbeds and nodules of green siltstone was assumed at a depth of about 450 to 650 m, and overlying a very fine grained to lithographic, non-porous, argillaceous to shaly limestone at a depth of about 650 to 840 m. The limestone is assumed to be horizontally bedded with horizontal fractures spaced 0.5 to 1 m, and vertical fractures spaced 10 m.

4 INDUCED FRACTURING OF ROCK

4.1 *Evolution of in situ conditions*

Rock fracturing is possible only under evolving in situ conditions. These conditions include the state of effective stress in the rock mass, and/or the rock mass properties. Changes in either of these conditions can increase or decrease the likelihood of rock fracturing. Conceptually, a change in effective stress can be represented by an evolving Mohr circle plotted in terms of effective normal stress and shear stress. Likewise, a change in rock mass strength can be represented by evolving Mohr-Coulomb or Hoek-Brown strength envelopes in this space.

4.2 *Failure mechanisms*

The mechanisms associated with rock failure include extensile (Mode I) fracturing under applied compressive or tensile loading, shear (Mode II) fracturing under high deviatoric stress conditions, and crushing under high isotropic compressive stresses. This latter case applies only to specific rock types with large porosity in the form of collapsible voids. Reactivation of existing fractures and faults is included in the first two categories.

4.3 *Significant features, events and processes*

4.3.1 *Excavation design*

The geometry, spacing, and orientation of an underground opening affect the nature of stress concentrations around the opening. Closed-form solutions are available to calculate tangential stresses around openings of circular, elliptical, and other shapes (e.g. Greenspan 1944). Depending on the aspect ratio of the opening and the in situ stress ratio, stresses exceeding the tensile and compressive strengths of the rock mass may develop at the tunnel periphery. The near-field stress concentrations around one opening may affect the stress field around adjacent openings if the spacing between openings is small enough. The relation between excavation design and rock fracturing, including the use of elliptical or oval-shaped openings, has been studied at the URL in Canada (Read & Chandler 1997).

Close to the tunnel periphery, the principal stresses are oriented tangential and orthogonal to the boundary. Mode I microcracks and small-scale fractures are expected to be oriented tangentially in a compressive stress field (possibly leading to spalling), or radially in areas of tensile stress. Small-scale near-field Mode II fracturing is expected in areas of high compressive tangential stress close to the periphery where confining stress is close to zero. These near-field microcracks and small-scale fractures cannot progress far from an underground opening in a compressive stress field because the minimum principal stress increases to far-field conditions within a short distance from the opening. Therefore, these near-field fractures are not expected to contribute to large-scale fracturing of the rock mass.

Where the option exists, tunnels are commonly oriented parallel to the maximum principal stress to reduce the stress concentrations around the completed opening. A consequence of orienting tunnels parallel to the maximum principal stress direction is the increased likelihood

of strength degradation around the tunnel periphery due to three-dimensional stress path effects ahead of the advancing tunnel face (Read et al. 1998). Possible considerations to mitigate these effects include pilot-and-slash excavation sequencing, and altering the shape of the tunnel face (Read 1994). These effects are not expected to lead to large-scale fracturing in competent rock.

4.3.2 *Excavation method*

Excavation methods proposed for a DGR include drill-and-blast and mechanical boring for both horizontal and vertical openings. Experience with both of these methods (Read & Martin 1996, Read & Chandler 1997, Emsley et al. 1997) suggests that non-explosive excavation techniques produce less near-field fracturing, particularly in rock masses with high strength to stress ratios. In addition to eliminating dynamic stress and gas pressure effects that can destroy rock cohesion, the smoother geometry of bored openings compared to blasted openings also reduces the likelihood of localized stress concentrations. Hence, bored openings are expected to sustain higher compressive boundary stresses compared to blasted openings. Likewise, for openings expected to experience localized tensile stress concentrations at their periphery, mechanical excavation is less likely to induce discrete macro-scale tensile fracturing compared to blasting (Read et al. 1998a). The use of pilot-and-slash excavation sequencing may also reduce the likelihood of near-field fracturing.

4.3.3 *Heat generation*

Heat generation due to UFC placement in underground openings will cause the overall temperature of the repository horizon to increase with time. This increase in temperature will cause thermal expansion of the rock mass and increase the isotropic component of stress in the horizontal plane. The thermally-induced stress change is directly proportional to Young's modulus, which can vary with mean or confining stress (Chandler 2001). Thermal expansion may lead to localized spalling or may weaken the rock mass in the vicinity of underground openings. In a tensile regime, it may reduce tensile strength of the rock mass through micro-crack development (Read 1994). The shear modulus of the rock mass may also be reduced by increasing the crack volume through differential expansion of mineral grains. The effects of thermal-mechanical stress path on the excavation-induced fracturing around underground openings in crystalline rock have been investigated in situ (Read et al. 1997a, Andersson 2007) and in other rock types. These effects alone are not expected to result in large-scale fracturing.

Heating may also induce significant pore pressure increases in the rock mass as a result of thermo-poroelastic effects. If these pore pressures are high enough to overcome the minimum principal stress and the tensile strength of the rock mass, then extensile fracturing is possible. Thermo-poroelastic effects have been studied at the URL in Canada (Read et al. 1997a, Martino and Chandler 1999, Detournay & Berchenko 2001). In situ at the URL, the undrained pore pressure increases at a rate of about 400 kPa/°C. While thermo-poroelastic effects are not anticipated to be an issue, further study of these effects is required to support the RA.

Based on studies at the URL (Chandler et al. 1992) and elsewhere, heating is expected to cause desiccation of clay-based buffer materials. These same types of effects are expected in clay shale. Desiccation resulting from ventilation also has the potential to cause near-field fracturing in clay shales (Read 2008). This phenomenon can be limited through the use of shotcrete or lining installation. Exposure of the rock mass to freezing temperatures may also lead to near-field deterioration.

Other effects of heating include reduction in the threshold for subcritical stress corrosion cracking (Wilkins et al. 1984), and in the associated thresholds for fracture initiation and propagation (Martin & Chandler 1994).

4.3.4 *Groundwater effects*

The location of the groundwater table and the pore pressure profile with depth are important site characteristics in determining the potential for large-scale fracturing. Perched water tables or over-pressured horizons may create locally unique conditions in layered systems such as the se-

dimentary stratigraphy of the Michigan Basin. The pore pressure gradient is also affected by the fluid density, which for saline conditions may significantly exceed that of fresh water.

If there is interconnection between horizons of different salinity, or if fresh water is introduced into smectite-rich marine shales, there is a possibility of swelling of the shale and associated deterioration of the shale strength. This phenomenon may create near-field fracturing and rock failure if not prevented or controlled. Likewise, swelling of clay materials in faults and fractures can generate high swelling pressures and result in significant strength loss (Brady & Brown 1985). Cycles of wetting and drying of the rock mass may lead to slaking in some materials, such as clay shales, resulting in deterioration of the rock mass. These effects can be controlled through DGR design (e.g., grouting, linings, and avoidance of known fracture zones).

4.3.5 *Chemical alteration of rock*

Chemical alteration of the rock mass may occur as a result of circulating fluids in permeable zones such as faults and cataclastic zones. This alteration may degrade the rock to clay-like material with relatively low strength. Although this is typically a very slow process measured in geological time, it may result in decreasing shear strength on existing faults and fracture systems over long periods of time. Depending on stress conditions over the same time period, it may be possible to reactivate existing fault and fracture systems. The change in permeability that accompanies severe alteration may also contribute to changes in pore pressure distribution and potential hydraulic pathways within the rock mass (e.g. channelized groundwater flow within fracture Zone 2 at the URL). These effects are not anticipated to lead to new large-scale fracturing remote from existing faults or fractures, and may be remediated through the use of grouting of major fractures and faults to reduce hydraulic conductivity and water flow.

4.3.6 *Glaciation and permafrost*

Glaciation may impose several changes on in situ conditions. Glacial loading is expected to apply a surcharge to the ground surface, effectively increasing the vertical stress, and to a lesser extent, the horizontal stresses at depth. Depending on ice thickness, the change in stresses may alter the environment enough to promote reactivation of preferentially-oriented fractures. In a thrust fault regime, where the vertical stress is the minimum principal stress, the induced stress changes are likely to reduce the deviatoric stress, and create more isotropic conditions. This effect is expected to reduce the likelihood of fracture development.

Depending on the shape of the glacial front, the leading edge of the advancing or retreating 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 beneath the applied load. Depending on the rate of advance of the glacial ice, excess pore pressures may also be generated. In addition, near-surface freezing and eventual thawing may promote long-term disaggregation of the rock mass. These effects are considered near-surface effects, and are not anticipated to affect the repository level. Confirmatory analysis would help quantify the depth to which these effects may extend.

Glacial ice will impose a sub-zero temperature boundary at surface, and will cool the rock mass with time, the rate depending on the thermal conductivity of the rock mass. This effect may create permafrost conditions, which may offset to some extent the thermally-induced stresses and pore pressures caused by heating of the DGR. Cooling of the rock mass was not assessed directly in this study.

4.3.7 *Discontinuities*

Discontinuities in the rock mass may act to concentrate stresses or to perturb the in situ stress field (Martin et al. 1994, Martin & Chandler 1993). Movement along these features may reorient the stresses for a considerable distance from the feature, and may create unique stress domains at a site (Martin 1990). Existing faults are more likely to be reactivated than new fractures forming if the fault regime does not change (Fairhurst et al. 1996). Movement along existing faults may promote other types of fracturing such as extensile jointing due to flexure of the overlying displaced rock volume (Martin et al. 1994). Shear faults of this type are expected to

act as boundaries across which extensile cracks will not penetrate due to the lack of stress relief below such faults (Fairhurst et al. 1996).

4.3.8 *Material properties contrast*

In layered systems, such as the sedimentary sequence in the Michigan Basin, stress changes within the system caused by heating or glaciation may create or contribute to a non-uniform stress distribution with depth if the layers have contrasting properties, specifically Young's modulus and Poisson's ratio. Differential straining of adjacent rock layers may result in relative shear displacement along the interface between layers, or extensile cracking in the stiffer layer. This type of phenomenon is a concern in the petroleum industry where steam-assisted processes are used to extract heavy oil or bitumen from formations underlying shale caprocks. Depending on the strain localization that occurs along the interface, it is possible to generate shear fractures along the interface and/or along inclined heterolithic strata within the shale.

In crystalline rock, the presence of biotite-rich layers in the rock mass may represent a contrast in strength properties. Xenolithic layers in the Lac du Bonnet batholith at the URL have acted as preferred weak planes along which shearing has occurred (Everitt & Lajtai 2004). Likewise, anisotropic strength and deformation properties are common to both crystalline and sedimentary rocks, particularly shales. These property contrasts affect the initiation and propagation of fractures within the rock mass. These effects should be considered in detailed analyses of specific DGR options to support the RA.

4.3.9 *Seismicity*

Seismicity may occur naturally due to tectonic activity, or as a result of effective stress changes within the rock mass. Seismicity is a concern with respect to the creation of new fractures or reactivation of faults. Dynamic stresses generated by seismic events may generate fracturing or localized rock failure near openings. However, provided that seismically active faults are not in the immediate vicinity of underground openings, risk to safety from earthquake damage underground during DGR construction and operation is not considered significant (Ates et al. 1994).

The seismic potential in much of the Canadian Shield is very low compared to other parts of North America (AECL 1994). A probabilistic seismic hazard evaluation of the Canadian Shield in northwest Ontario (Atkinson & McGuire 1993) indicated that, as long as no seismically active fault was within 50 m of a DGR, the annual probability of an earthquake capable of causing fracturing that would reach the disposal rooms of the vault was less than $5 \cdot 10^{-7}$. This probability was reduced to effectively zero for offset distances of 1000 m for a 2 km long active fault, and 200 m for a 5 km long active fault, respectively.

In terms of induced seismicity, Ortlepp (1992) assessed the risk of rockbursting at the URL, and at a hypothetical repository constructed in similar conditions. Strain-bursting similar to the spalling observed at the URL (Read & Martin 1996) is expected at or very close to the tunnel periphery in some circumstances, particularly if blasting is not used to destress the near-field rock by creating some damage. Fault-slip is not anticipated because of the absence of major faults at depth and the small extraction ratio (about 0.25) associated with a typical DGR design. Ortlepp (1992) concluded that there is no significant rock burst risk associated with further development of the URL, or with the creation and operation of a DGR in the same environment.

4.3.10 *Heave*

Heave of the rock mass overlying the repository horizon is expected as a result of heating the rock mass. This displacement tends to be upward near the centre of the repository, with a lateral component towards the edges of the repository. The maximum shear stresses generated by heave are located above the edges of the repository. If there are preferentially oriented weaknesses in the rock mass, areas of shear stress may generate near-surface shear fractures under certain conditions. Heave of the rock mass will also decrease the lateral stresses in the near-surface rock mass to the point where sub-vertical extensile fracturing may occur to some depth. It is inconceivable that these tension cracks would penetrate to the repository level as confining stress increases with depth and with increased temperature near the repository. However, in

some cases extensile fractures may provide near-surface connection between isolated groundwater systems where layered stratigraphy exists. This could be a particular concern with respect to salt or anhydrite strata. Although unlikely for small displacements, heave at surface may disrupt the natural surface drainage patterns and alter the groundwater system accordingly.

4.3.11 Backfill/rock interaction

Clay-based buffer and backfill is expected to swell once saturated, and generally provide an internal swelling pressure of between 100 kPa and 4 MPa on the periphery of boreholes and placement rooms. The rate of swelling is dependent on water availability which is in turn a function of the rock mass connected permeability and pore pressure distribution. Studies at the URL (Chandler et al. 1992, Dixon et al. 2001) have shown that buffer saturation is a slow process, and that reliance on swelling pressure in placement room design is not a conservative assumption. Results from experiments at the URL (e.g. Read & Martin 1996, Read et al. 1997a) demonstrate clearly that a small confining pressure of 50 kPa is sufficient to prevent ongoing strength degradation through microcracking at or near the tunnel periphery. The weight of buffer and backfill materials alone should be sufficient to prevent further degradation of rock strength below excavations. However, intentional gaps between the rock and buffer/backfill materials in certain borehole placement designs or at the crown of excavations in an in-room design may lead to some degradation of the rock mass before the gaps close. In cases where there is initially no contact pressure by the swelling clay, the beneficial aspects of small confinement for the prevention of rock damage will not be present until the gaps close. Support pressure from backfill was not taken into account in the analyses in this study, but it is expected to reduce the likelihood of fracturing.

5 SUPPORTING ANALYSIS

5.1 Methodology and criteria

Analyses were conducted to examine possible large-scale fracturing in the far-field and in the near-field (Read 2008). In the far-field scenarios, a Hoek-Brown strength envelope corresponding to the long-term strength of the rock mass was used as the threshold for new fracturing. A Mohr-Coulomb envelope was used to check for slip along pre-existing faults or large-scale fractures, a necessary pre-cursor to the initiation and propagation of new extensile wing cracks and Mode II shear fractures from existing fractures. Both of these criteria were plotted in shear-normal stress space to compare to Mohr circles depicting various in situ stress states associated with construction and operation of a DGR. Where a Mohr circle intersects one or more of these envelopes, fracturing (or re-mobilization of an existing fracture or fault) is expected. If slip on an existing fracture or fault is indicated, further analysis could be undertaken to assess the likelihood of initiation and propagation of new extensile wing cracks or Mode II shear fractures using a general criterion based on a ratio of $\sigma_3'/\sigma_1' \leq 0.05$ (Read et al. 1998).

Near-field analysis of the various DGR options in the three rock types was undertaken using Hoek-Brown strength ratios corresponding to near-field rock compressive and tensile strength to assess the onset of small-scale near-field fracturing, and a Mohr-Coulomb criterion based on the effective stress ratio to assess the likelihood and extent of the zone of possible slip on near-field fractures. This second set of analyses assumes that existing fractures are cohesionless and oriented at a critical angle to the minimum principal stress in the near-field such that the shear stress along the plane is maximized. The critical effective principal stress ratio associated with the Mohr-Coulomb envelope for fracture slip is given by:

$$\frac{\sigma_3'}{\sigma_1'} = \frac{1 - \sin(\phi)}{1 + \sin(\phi)} \quad (1)$$

where ϕ is the friction angle of the fracture plane.

By comparing this ratio with stress conditions around an underground opening, the extent to which fractures within the excavation damaged zone can propagate under different loading scenarios can be approximated. This analysis does not account for changes in near-field material

properties or changes in excavation shape as a result of tunnel instability. However, it provides a preliminary estimate of the maximum distance to which a small-scale near-field fracture may extend under specific thermal-mechanical loading conditions. This analysis does not account for thermo-poroelastic effects that may generate excess pore pressure at or near the fracture tip; these effects should be examined in more detailed analysis to support the RA.

5.2 Far-field analysis

The far-field analysis scenarios considered include a DGR at depths of 500 and 1000 m in crystalline rock typified by Lac du Bonnet granite, and a DGR at depths of 500 and 750 m in sedimentary rock typified by Queenston Formation shale and Lindsay Formation limestone, respectively. Rock properties, in situ stress conditions, and pore pressure conditions were derived from published literature and unpublished information from NWMO. Stress conditions associated with ambient, thermal, glacial, and glacial+thermal conditions were calculated using closed-form solutions. Details of the input parameters and analysis results are described by Read (2008). An example of results from the glacial+thermal scenarios at 500 and 1000 m depth in crystalline rock is shown in Figure 2.

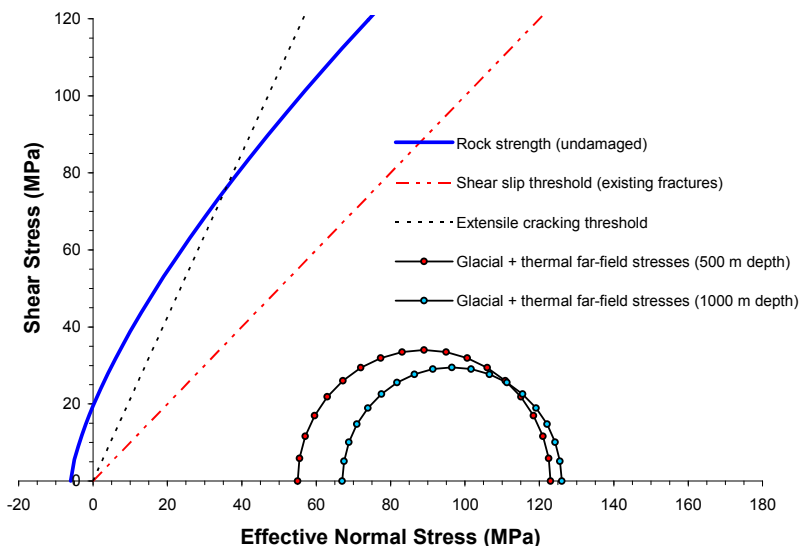


Figure 2. Far-field analysis of a DGR in crystalline rock under glacial+thermal conditions (Read 2008).

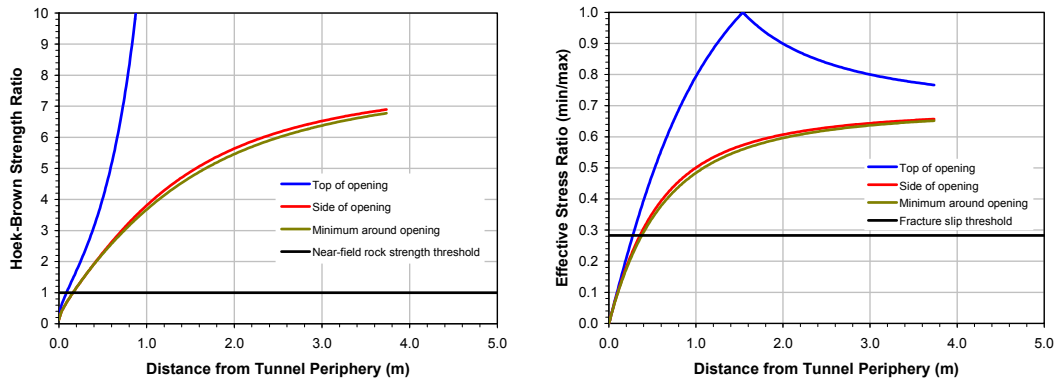


Figure 3. Near-field analysis of an placement borehole in a KBS-3V-type DGR at 500 m in shale under ambient conditions with placement room parallel to maximum horizontal stress (Read 2008).

5.3 *Near-field analysis*

To investigate the likelihood of large-scale fracturing resulting from near-field conditions associated with the various DGR designs, 240 individual analyses of DGR excavations in crystalline and sedimentary rock were conducted (Figure 3). Results of these analyses are summarized by Read (2008). The cases include six loading scenarios for four DGR designs at two different depths in both crystalline and sedimentary rock. Separate scenarios were analyzed for openings oriented parallel and perpendicular to the maximum principal stress direction.

6 DISCUSSION OF RESULTS

The analyses conducted as part of this study demonstrate that the key factors controlling large-scale fracturing and faulting are the effective in situ stress state, and the rock mass strength and deformation properties. The in situ stresses in the crystalline and sedimentary rock scenarios considered represent thrust fault regimes, with the minimum principal stress vertical. Without a substantial decrease in effective vertical stress or increase in effective horizontal stress, the current deviatoric stresses are insufficient to initiate and propagate new fractures or to remobilize existing fractures in the far-field.

Heating of the repository level generates an increase in horizontal and (to a lesser extent) vertical stress. The magnitude of the stress change is directly proportional to Young's modulus and thermal expansion coefficient of the rock mass. The calculated stress changes in crystalline rock are significant, whereas those in limestone are less significant, and those in shale are almost negligible. Thermally-induced stresses increase deviatoric stress in all cases. However, even with the increase in stresses, the calculated stress states are insufficient to initiate and propagate new fractures or remobilize existing fractures in the far-field.

Glaciation causes a significant increase in the vertical stress component, and a minor increase in the horizontal stress components. For the crystalline rock scenario at 1000 m depth, this increase in the vertical stress reduces deviatoric stress, but does not alter the thrust fault regime (i.e. the vertical stress remains the minimum principal stress). The effect is to reduce the potential for fracturing. For the sedimentary rock scenarios at 500 and 750 m depth, the increase in the vertical stress component alters the stress regime, with the major principal stress switching from horizontal to vertical (i.e. a normal faulting regime). However, anticipated stress conditions before or during glaciation are insufficient to mobilize thrust faults at any angle, and stress ratios are insufficient to generate new fractures in the far-field.

The combined thermal and glacial stresses tend to reduce the overall deviatoric stress and increase the mean stress, effectively reducing the likelihood of new fracture initiation and propagation, or remobilization of existing fractures or faults. For the crystalline rock and limestone scenarios, the combined loading represents a thrust fault regime. For the shale scenario at 500 m depth, the combined stresses represent a normal fault regime with the maximum principal stress vertical. This alternation between fault regimes changes the definition of a preferentially oriented fracture or fault over time. Nonetheless, deviatoric and confining stress conditions at depth are insufficient to generate new fractures or fracture slip in the far-field.

Near-field thermal-mechanical analyses of the various DGR concepts in the different rock types show that some excavation damage is expected near the excavations in all cases owing to the zero confining stress at the periphery of the underground opening. DGR designs with intersecting openings (e.g. the in-floor borehole concept) create higher local stress concentrations than openings of either elliptical or circular cross-sectional geometry. The in-floor borehole design results in predicted spalling in the borehole and uplift in the invert of the placement room. Damaged near-field rock presents a design issue for sealing of placement boreholes and excavations but does not provide conditions for large-scale fracture propagation. The extent of the near-field effects are limited by the stresses and stress gradients to within about 2 m around underground openings; large-scale fracturing resulting from propagation of fractures within the damaged zone is not considered plausible without an additional driving mechanism such as thermally-induced hydraulic fracturing.

Analyses to date, with the exception of a preliminary simulation of thermo-poroelastic effects around a repository in granite (Chandler 2001), have generally not accounted for the possible

generation of significant pore pressures as a result of heating the rock mass. This appears to be the only viable mechanism by which effective stresses can be reduced to the point where hydraulic fracturing is possible. However, unstable propagation of new fractures by this mechanism would require a low permeability rock mass, groundwater flow to the fracture and relatively uniform conditions in the rock mass through which the fracture propagates. Fractures initiated in the near-field by this mechanism are likely to be limited by the near-field stress gradients around underground openings. Therefore, the thermal propagation of natural hydraulic fractures (Detournay & Berchenko 2001) is a potential issue only for low permeability, intact rock several metres or more away from the underground openings. This is a topic for additional research to help quantify the likelihood of large-scale fracturing.

In the absence of large thermally-generated pore pressures, none of the conceived scenarios produce stress conditions that would result in the initiation and propagation of new fractures, or remobilization of existing fractures. Specifically, although glacial events have occurred subsequent to fracturing at the URL, they have had little or no effect on propagation of subvertical fractures (Everitt & Brown 1994). It is anticipated that these types of fractures will remain dormant in the absence of the types of events required to radically change the stresses and topography, and that the existence of thrust faults at the base of these subvertical features will preclude vertical propagation (Fairhurst et al. 1996).

This study corroborates findings of Martin et al. (1994) who concluded, based on the original AECL placement designs, that large-scale Mode I fracturing was not likely given the compressive stress regime at the URL. Without a significant erosional event, the fault regime in granite was considered unlikely to change in the foreseeable future. Although thermal loading will increase the deviatoric stress, glaciation will reduce deviatoric stress and increase the mean stress, thus reducing likelihood of future fracturing. Martin et al. (1994) emphasized that in situ stresses can vary considerably near existing faults and fracture zones, so careful site characterization is critical to assess the likelihood of large-scale fracturing.

An expert panel convened in 1994 to investigate the possibility of fracture propagation caused by a repository in the Canadian Shield (Fairhurst et al. 1996) concluded that the existing thrust faults would prevent the development of new fractures or faults. Any future dynamic or quasi-static faulting in the vicinity of the URL would occur by slip along the existing thrust faults. In the event of slip along the faults, any new secondary fracturing would be limited to the existing near-field fractured zone, and would be on the order of 1 m or less due to the existence of high compressive stresses parallel and normal to the thrust faults. Heating was considered unlikely to produce significant new fracturing but could produce small amounts of slip on existing thrust faults located within tens of metres of the repository. The panel considered it unlikely that future seismic activity on the existing faults would produce an earthquake greater than 5.0 Richter magnitude, and that associated underground accelerations would not adversely affect the integrity of the rock mass. Any earthquake in the URL environment would have a thrust fault mechanism and would likely reduce pore pressure within a radius of several fault lengths for a period in the order of months before and after the earthquake. Given that the tectonic environment at the URL has been stable for at least 400 Ma, the panel concluded that no additional fracturing sufficient to compromise the integrity of a repository located several tens of metres from the thrust fault is likely to occur in the next 100,000 years (0.01 Ma).

None of the potential sources of fracturing identified in this study is expected to produce either subvertical fractures that extend more than 100 m below surface (i.e., beyond the near-surface zone of extension caused by heave) or more than a few metres from locally activated faults. Any anticipated stress conditions within the rock mass distant from the surface or faults are well below those strength criteria that must be exceeded to induce large-scale fracturing.

7 CONCLUSIONS

Based on this study, it is concluded that the RA is supported by both the analysis results summarized by Read (2008) and practical observations from the URL and elsewhere. The primary conclusion from this study is that the development and propagation of large-scale fracturing either between repository rooms, or between the repository level and other remote natural hydraulic pathways, is implausible. Information reviewed as part of this study supports the RA.

The applicability of the RA to potential repository environments should be framed within the context of this study. For sites with rock mass properties or in situ conditions that differ significantly from the specific cases considered in this study, the RA provides an approach to assess the potential for large-scale fracturing. The essence of this approach is first to define strength criteria that must be exceeded for large-scale fracturing to occur (e.g. intact rock strength and slip along fractures), second to define expected stresses within the rock mass for given scenarios (e.g. excavation, heating, and glaciation), and then test the criteria using an accepted approach (e.g. Mohr circles). Finally, the RA highlights the need for thorough characterization of each potential DGR site to determine the in situ conditions, rock mass properties and the degree of variability and heterogeneity at the site.

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