Compendium of Research, Development and Demonstration – Results from a Canadian Underground Research Laboratory

Grant Su, Geoscience Technical Specialist

Technical Meeting on the Compendium of Results of Research, Development and Demonstration Activities Carried Out at Underground Research Facilities for Geological Disposal

Gyeongju, Republic of Korea

September 11–15, 2017

e-Doc 5328850

nuclearsafety.gc.ca

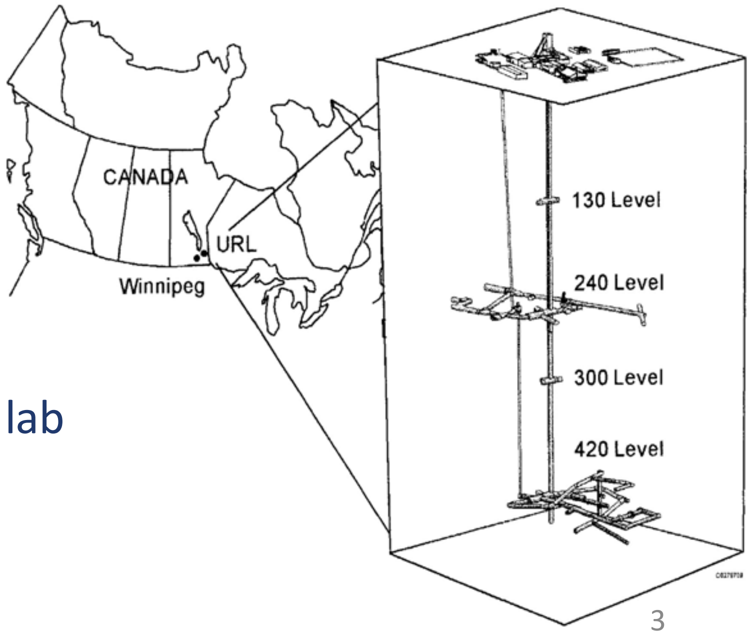
CANADA 150

Content

- Overview of Atomic Energy Canada Limited (AECL) Underground Research Laboratory (URL)
- Geological conditions of the URL
- Key Research, development and demonstration (RD&D) activities carried out at the URL
- Main results and key learning points of RD&D

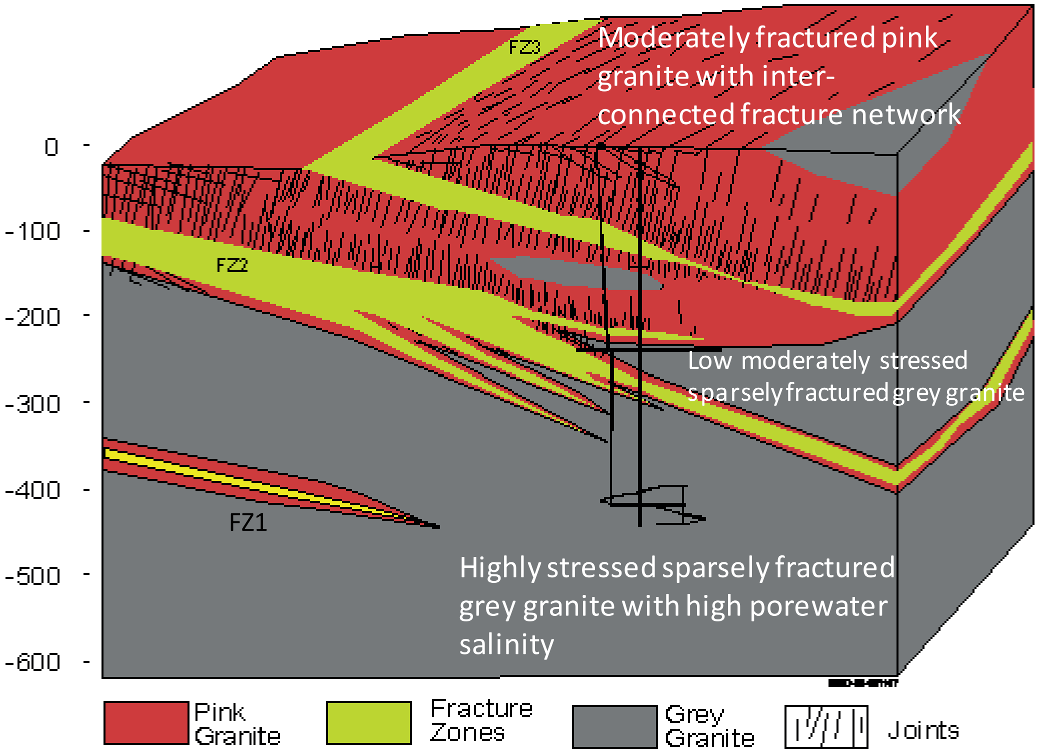
Overview of AECL URL

- 1963 – AECL builds the Whiteshell Laboratories nuclear research facility
- 1980 – AECL gets the go-ahead to build the URL
- 1983 – Construction of the URL begins
- 1985 – Main shaft excavated to 255 m depth
- 1987 – Initial development of 240 m level
- 1988 – Main shaft excavated to 443 m depth
- 1989 – Excavation of the 420 level access tunnel
- 1990 – Vent raise construction completed
- 1998 – Work begins to decommission the Whiteshell lab
- 2003 – Closure of the URL is announced
- 2006 – Work begins to close the URL
- 2010 – The URL is permanently closed

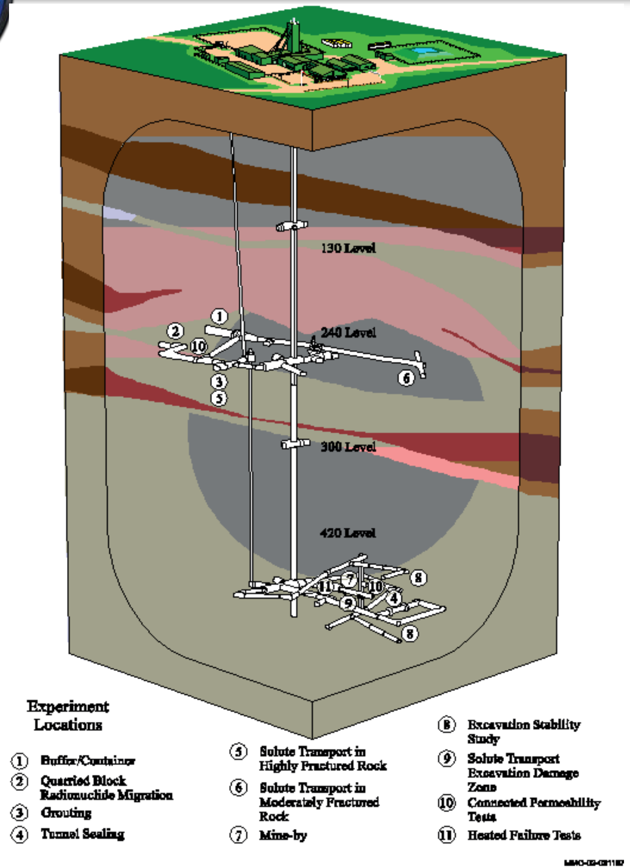


Geological and Hydrogeological Conditions

- The URL is situated on the Lac du Bonnet batholith, a large granitic pluton
- Three major low-dipping fracture zones control the large-scale patterns of groundwater movement and groundwater chemistry
- Rock mass below 300 m was found to be relatively unfractured with fracturing more pronounced near the surface
- Complex spatial pattern of hydraulic conductivity within each of the fracture zones



Key RD&D Activities Carried Out at the URL



- Surface and underground characterization
- Groundwater and solute transport
- *In situ* stress conditions
- Temperature and time-dependent deformation and failure characteristics of rock
- Excavation techniques to minimize damage to surrounding rock and to ensure safe working conditions
- Buffer and container experiments
- Shaft sealing experiments

Main Results and Key Learning Points of Research, development and demonstration (RD&D)

Validation of Groundwater Flow Modelling

- Objective: To determine if the responses of the groundwater system in the rock around the shaft could be successfully predicted by the three-dimensional, finite element model of MOTIF, and a finite difference code of SWIFT, based on the conceptual model of the hydrogeology of the site and calibrated to the hydrologic data obtained from tests and measurements made within the monitoring system before shaft sinking began
- These models were used to predict the groundwater responses at 171 locations in the surrounding rock mass due to the construction of the shaft to a depth of 255 m
- Main findings: MOTIF model slightly overestimated groundwater inflow rates to the shaft but agreed well with the trend of flow rate with time, while SWIFT model predicted lower seepage rates than measured and did not agree well with measured flow rate with time

In Situ Stress Test (1)

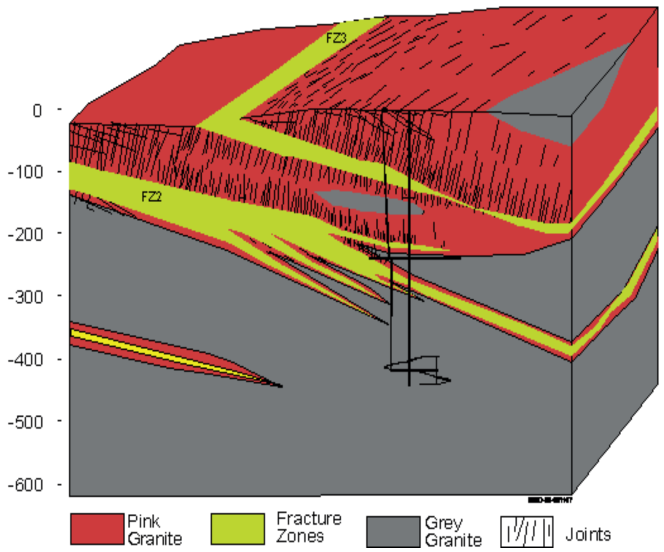
- Objective: To evaluate techniques for determining the *in situ* stresses in rock and to investigate the factors which influence stress magnitude and variability
- Context of experiments
  - 350 far-field overcore tests and approximately 80 hydraulic fracturing measurements conducted at the URL site
  - observations of shaft wall failure, microseismic sourcing, shaft convergence measurements, hydraulic fracture reopening analysis, doorstopper overcoring, and under-excavation stress determination were conducted

In Situ Stress Test (2)

- Main results
  - hydraulic fracturing and overcoring stress determination methods can produce acceptable data under low-and intermediate-stress conditions
  - these conventional methods cannot be used in regions of high horizontal stresses at depth
- Key learning points
  - determination of a stress tensor in rock is an iterative process which builds upon successive stages of stress information collection
  - confidence in the calculated *in situ* stress tensors is not obtained through any individual techniques but by examining the results from a variety of measurements and observations

Solute Transport in Highly Fractured Rock Experiment (1)

- Objective: To develop and demonstrate methods for estimating the solute transport properties in fracture zones at local and regional scales under different testing conditions for the development of groundwater flow and solute transport models



Solute Transport in Highly Fractured Rock Experiment (2)

- Context of experiments
  - phase 1: Seven groundwater tracer tests ranging in scale from 17 to 209 m were conducted in Fracture Zone 2 to examine scale- and directional-dependent solute transport properties
  - phase 2: A series of six tracer tests were conducted in Fracture Zone 2 at a smaller scale of about 20 m
  - phase 3: Large-scale tests were performed to help establish whether the solute transport properties within zones of intensely fractured rock are scale- or direction-dependent
  - the tests studied different test methods, examined the effects of flow direction and rate, and compared the transport behaviour of different tracers

Solute Transport in Highly Fractured Rock Experiment (3)

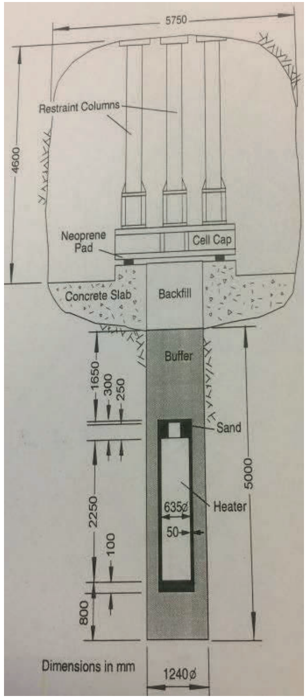
- Main results
  - at the larger transport scale, an averaging of the solute transport properties within the fracture zone occurs and the effects of large-scale permeability variations are important at the larger transport scale
  - the tracer breakthrough results obtained from different test methods were different
  - the tracer breakthrough results from one pair of two-well tests shown that the rate of tracer transport was not direction dependent between these two wells
  - two continuous recirculating tracer tests suggest that the media transport properties between two tested boreholes were unaffected by the flow rate

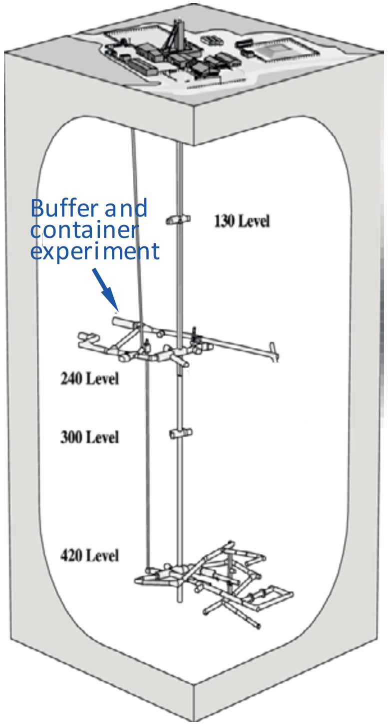
Solute Transport in Highly Fractured Rock Experiment (4)

- Key learning points
  - the equivalent-porous-media approach is probably suitable for modelling fluid flow and solute transport in the major fracture zone
  - development of an adequate transport model capable of describing all tests has been more difficult
  - colloid and conservative groundwater tracers behaved very similarly in terms of relative transport during these tests

Buffer and Container Experiment (1)

- Objective
  - evaluate and document the full-scale *in situ* performance of the reference buffer material under a realistic geologic setting and effects of heat
  - assess the survival of naturally present microbial populations in buffer material including survival under experimental conditions





Buffer and Container Experiment (2)

- Experimental setup
  - A 2 m high and 0.6 m diameter electric heater was placed within a 1.24 m diameter by 5 m deep borehole in granite and surrounded completely by sand-bentonite (50:50 by wt.) buffer material compacted *in situ*. The annulus of buffer material between the heater and the rock was 26 cm.
  - The heater was operated at a constant power setting to maintain the temperature of the heater surface at approximately 85°C.
  - The heater was turned off after 2.5 years of operation, and the heater and buffer material were removed.

Buffer and Container Experiment (3)

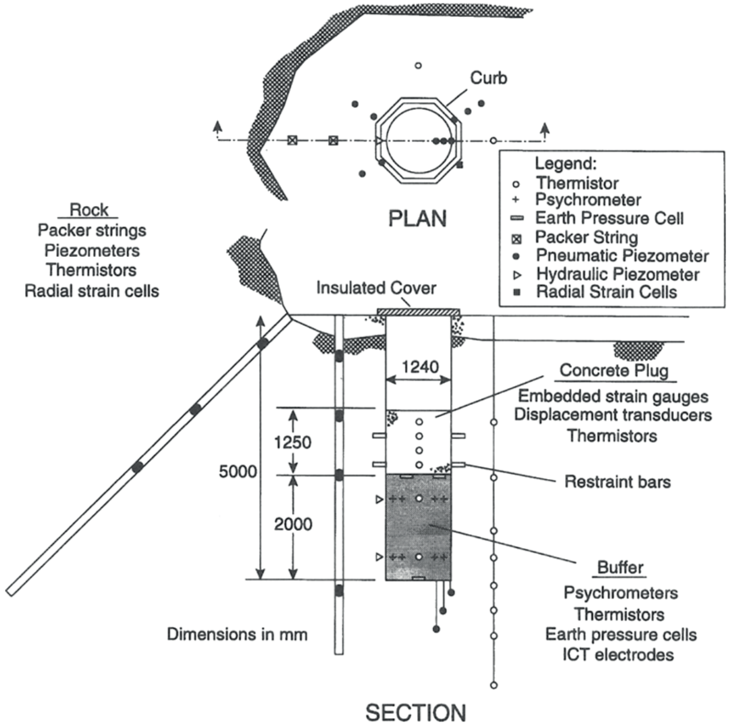
- Main results
  - Temperature drop across the annulus was 30°C.
  - Buffer material adjacent to the rock boundary was saturated while considerable drying of the buffer had occurred next to the heater. Upon removal of buffer, drying shrinkage was visibly evident by the presence of cracks extending radially to a maximum of 10 cm into the annulus and had no evidence of cracking beyond.
  - Upon resaturation, this cracked material regained the low hydraulic conductivity of the buffer which had never experienced thermal drying, illustrating the self-healing properties of the material.
  - An almost universal disappearance of all culturable microorganisms in buffer samples with a low (<15%) moisture content (corresponding to a water activity a_w of ~0.96) and a high temperature (50-60°C).
  - Moisture content was the main factor controlling the occurrence of viable organisms in this buffer material.

Buffer and Container Experiment (4)

- Key learning points
  - the reference bentonite/sand mixture compacted *in situ* to a minimum effective clay dry density of 1.21 Mg/m^3 could provide adequate thermal, hydraulic, and mechanical properties for the proposed repository
  - some time after disposal of waste containers, the area around the containers (i.e., the part of the buffer directly adjacent to the containers) would likely be devoid of microbial activity because of the redistribution of moisture as a result of the high temperatures associated with the waste container

Isothermal Test (1)

- Objective: To examine water uptake by the buffer material in the absence of thermal gradients
- Context of experiments
  - 2 m buffer material was placed at the bottom of a borehole 5 m deep by 1.24 m diameter overlain by 1.25 m thick concrete plug that provided a restraint to the buffer material
  - same types of instrumentation as in the Buffer/Container Experiment were installed in the Isothermal Test to monitor transient water uptake of the buffer material

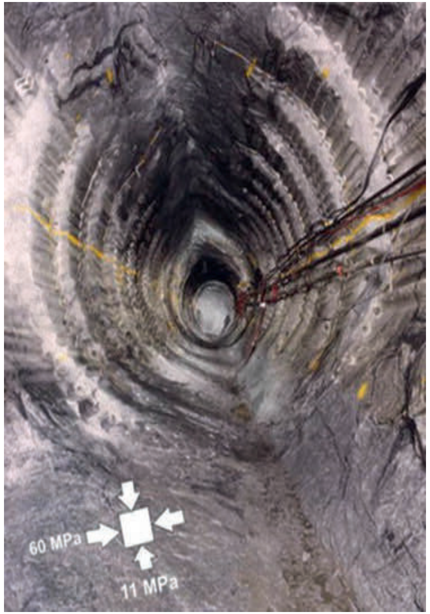


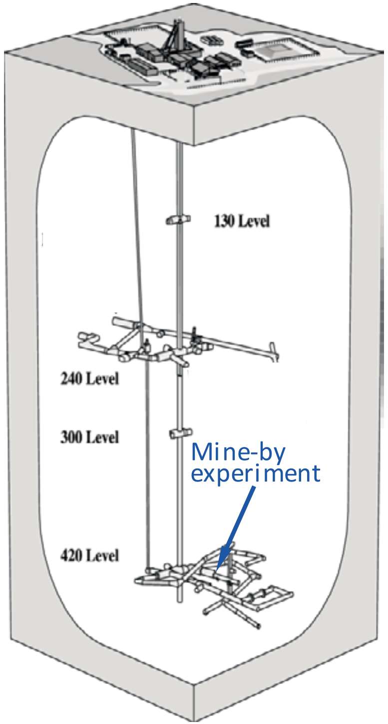
Isothermal Test (2)

- Main results
  - good correlation of the data was achieved between the different types of instruments installed
  - systematic variations in suction and moisture content within the buffer were monitored
  - the buffer closest to the rock showed lower suction or higher moisture content than the buffer in the center
  - the largest changes in suction and moisture content were located at the bottom corner of the test hole as a result of increased moisture availability from rock in both the vertical and horizontal directions
- Key learning points: Water uptake by the buffer material is immediate and the change in total suction with time is gradual and systematic

Mine-By Experiment (1)

- Objective
  - study progressive failure and the development of excavation-induced damage around a 3.5-m diameter circular tunnel





Mine-By Experiment (2)

- Context of experiments
  - conducted at the deepest level (420) of the URL, the experimental tunnel 415 was 46-m long, aligned subparallel to σ_2 and was excavated mechanically; the *in situ* stress ratio in the plane perpendicular to the Mine-By tunnel exceeded 5 to 1
  - instrumentation included extensometers and convergence arrays to measure displacement, triaxial strain cells to measure strains, and thermistors to measure temperature; acoustic emission/microseismic (AE/MS) instrumentation to monitor the damaged zone development
  - over 500 data channels were monitored as the excavation progressed

Mine-By Experiment (3)

- Main results
  - *in situ* crack initiation occurred at about 0.3 of the undisturbed lab strength σ_c and spalling initiated when the tangential stress around tunnel reached 0.5 to 0.6 of σ_c
  - once failure initiated near the tunnel face, progressive development of a v-shape around the tunnel occurred, which was similar to those observed in borehole breakouts
  - the depth of intense fracturing at the notch tip was less than 30 cm
  - fracturing beyond the stable tunnel perimeter was essentially non-existent at a lateral distance of 50 cm to either side of the north tip

Mine-By Experiment (4)

- Key learning points
  - the orientation of the principal stresses relative to the tunnel axis can affect the pattern of excavation damage observed *in situ*
  - the rock strength immediately around the test tunnel is reduced significantly at very small levels of damage
  - from observations of damage and from AE/MS results, the highly crushed rock at the notch tip and the fractures forming the thin slabs along the flanks of the V-shaped notch would be the locations with the greatest potential to contribute to contaminant transport

Connected Permeability Experiments (1)

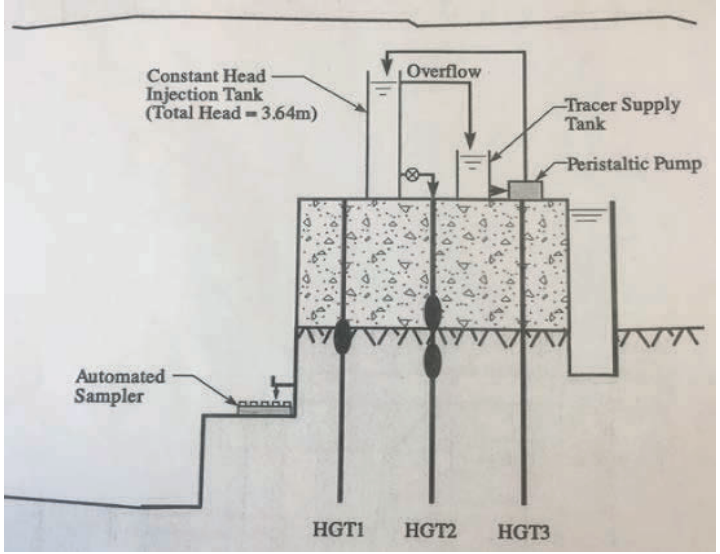
- Objective: To evaluate the hydraulic properties of the zone of rock damage in the floor of excavation at the URL
- Context of experiments
  - one test was conducted in a tunnel excavated using a drill-and-blast technique at the 240 level, a second test was conducted in the mechanically excavated Mine-By tunnel
  - hydraulically conductive water flow experiments were conducted to evaluate the fracture connectivity

Connected Permeability Experiments (2)

- Main results
  - The blast-induced damage beneath the floor of excavation was less than 0.4 m in depth and was found to be largely unconnected from one blast round to the next.
  - The stress concentrations around the mechanically excavated Mine-by tunnel produced a small zone of hydraulically connected fractures that potentially extended over the entire length of the excavation. The volume of this damage zone is about 1 percent of total excavated volume, but its hydraulic conductivity was increased 6 or 7 orders of magnitude.
- Key learning points: The hydraulic pathway could be interrupted by keying a low permeability bulkhead through the damaged rock zone and into the undamaged rock.

Excavation Damaged Zone (EDZ) Tracer Experiment (1)

- Objective
  - to characterize the physical solute transport properties (permeability, transport porosity, and dispersivity) of the EDZ of the Mine-By tunnel
- Context of experiments
  - the experiment was performed at a constant head/continuous source injection test at a scale of 1.5 m in a region of EDZ previously characterized during the Connected Permeability Experiment



EDZ Tracer Experiment (2)

- Main results
  - measurements of permeability through the EDZ correspond well with those measured during the Connected Permeability Experiment
  - hydraulic conductivity, transport porosity, and dispersivity were estimated from the experimental data
- Key learning points
  - the main flow pathway within the EDZ in the floor of the tunnel was within the highly damaged zone located at the tip of the breakout notch

Heated Failure Tests (1)

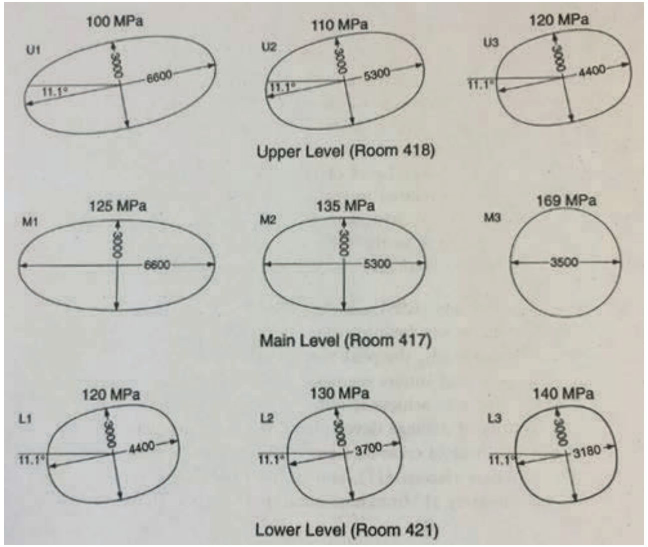
- Objective: To examine the effect of thermal loads on the extension of excavation damage in highly stressed and sparsely fractured rock
- Context of experiments
  - the tests were located in a well-characterized portion of the floor of the Mine-By tunnel (room 415) at the 420 level
  - heated the rock surrounding a 600-mm diameter borehole to temperatures of about 85°C

Heated Failure Tests (2)

- Main results
  - the rock failed almost exactly at the *in situ* strength of undamaged rock based on calculated stress changes due to thermal loads
  - the radial extent of the existing breakouts only marginally increased during heating
- Key learning points
  - the rock strength under thermal loads is consistent with the observations of *in situ* rock strength from the Mine-By Experiment
  - the formed EDZ will not be driven outwards as the rock warms in a vault environment
  - use of sealing materials will reduce the likelihood of instability and will inhibit EDZ development

Excavation Stability Study (1)

- Objective: To evaluate tunnel stability and the extent of excavation damage in tunnels as a function of tunnel geometry and orientation, geology, and excavation method



Excavation Stability Study (2)

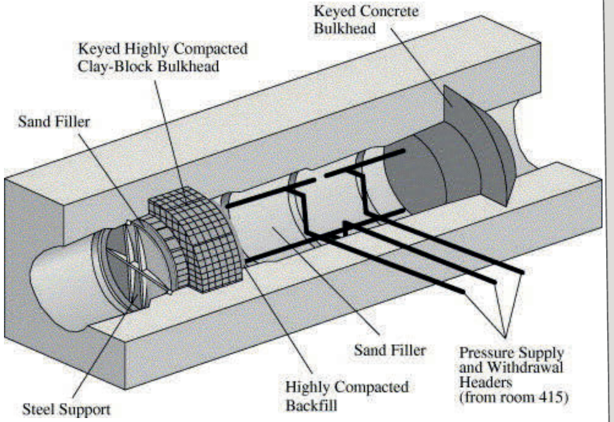
- Context of experiments
  - nine ovaloid and circular openings were excavated at the 420 level to achieve different boundary compressive stress concentrations and near-field stress distributions
  - each tunnel segment was excavated in the direction of the intermediate principal stress (i.e., subparallel to the Mine-By tunnel) using controlled blasting methods and mechanical excavations

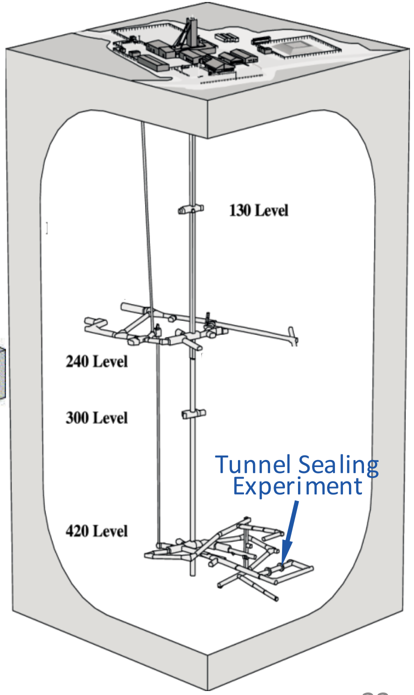
Excavation Stability Study (3)

- Main results
  - mechanically stable openings with a minimal EDZ can be excavated in the most adverse stress conditions at the 420 level of the URL
  - tunnel stability is sensitive to tunnel shape, variation in geology, and to a certain extent, the excavation method
  - the observed depth of visible damage (i.e., EDZ) ranged between 0 and 80 mm in the roof and sidewalls, and to a maximum depth of 120 mm in the floor
- Key learning points: The geometric design of the excavations is perhaps the most effective way of minimizing the extent of the EDZ around tunnels in highly stressed rock, and is more significant than the choice of excavation method (i.e., mechanical versus drill-and-blast)

Tunnel Sealing Experiment (1)

- Objective: To demonstrate technologies for construction of bentonite and concrete bulkheads, to evaluate the performance of each bulkhead, and to identify the factors that affect the performance





Tunnel Sealing Experiment (2)

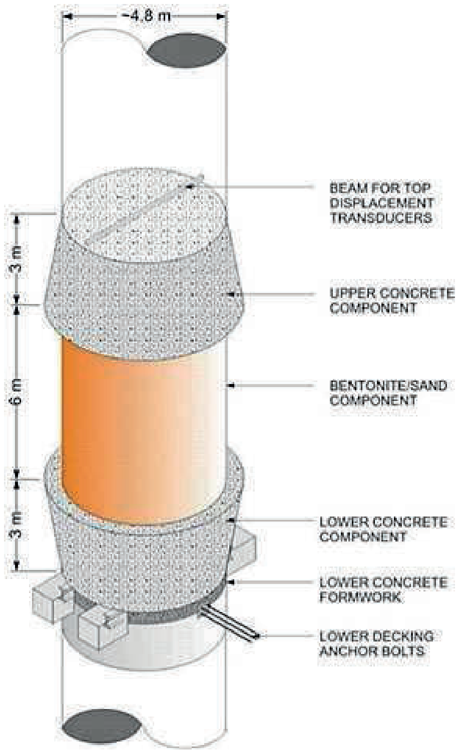
- Context of experiments
  - one bulkhead was composed of high-performance concrete and the other of highly compacted sand-bentonite material
  - the chamber between the two bulkheads was pressurized to approximately 4 MPa, representing the ambient pore pressures in the rock at a depth of 420 m
  - the seepage was monitored through and around each bulkhead as well as changes to the pore water pressures and to the flow directions in the intact rock, and stresses and displacements in each bulkhead
  - a second phase of the experiment involved heating the water in the test chamber between the two bulkheads to about 85°C, from which the effect of elevated temperatures on the various components of the sealing systems was investigated

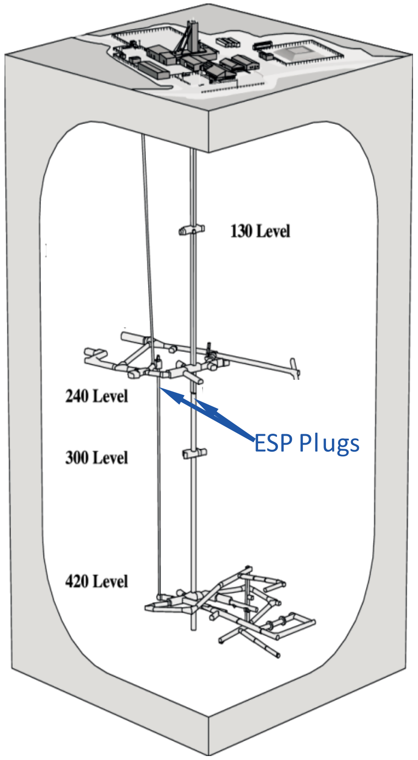
Tunnel Sealing Experiment (3)

- Main results
  - the EDZ development was decreased by application of a confining pressure either by filling with a material or by an applied hydraulic pressure
  - the keyed seals cut off or reduced flow through the EDZ, and the primary pathways were the rock-concrete and shotclay-rock interfaces
  - the applied thermal load in the clay bulkhead did not impact flow rate
  - heating did cause an expansion of the concrete that closed the interface aperture and decreased the flow rate
  - the clay bulkhead demonstrated the ability to self heal and adjust to differential displacements
  - the concrete bulkhead was able to withstand the loading from hydraulic pressure with minimal offset
- Key learning points
  - it is possible to construct functional clay and concrete bulkheads to seal tunnels and limit axial flow even under high hydraulic gradients

Enhanced Sealing Project (ESP) (1)

- Objective: Assess the ability to construct a shaft seal at the location of a water-bearing fracture, monitor water uptake by the bentonite clay component, monitor stress development within and surrounding the shaft seal and evaluate the seal's ability to restrict water flow across it





Enhanced Sealing Project (ESP) (2)

- Context of experiments
  - the seal is located at a depth of ~275 m, where the main shaft and vent raise intersect the ancient water-bearing, low angle thrust fault
  - 100 sensors installed in 4.8 m x 6 m main shaft plug
  - long-term monitoring sensors ran ~300 m vertically to data collection terminals
  - decommissioning of URL was completed in 2010 but the ESP that was started in 2009 is continuing to monitor a full-scale shaft seal

Enhanced Sealing Project (ESP) (3)

- Main results/observations
  - shafts are still filling and equilibrium conditions not reached
  - the outermost 0.5 m of clay-fill was saturated by mid-2014
  - substantial wetting occurred in the core during 2015 and 2016
  - a substantial pressure difference exists across the seal indicating the effectiveness (very low permeability) of the clay seal
  - the composite concrete – bentonite seal in the ESP is resisting water movement between the upper and lower shaft
- Key learning points
  - monitoring underground installations from a considerable distance is challenging and can prove very expensive

Questions?

Thank You!

Participate and Contribute!

CNSC CCSN

CANADA 150

- Visit us online
- Like us on Facebook
- Follow us on Twitter
- View us on YouTube
- Subscribe to updates
- Contact us