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TESTING OF A BENTONITE-BASED TUNNEL SEAL FOR USE IN A DEEP GEOLOGIC REPOSITORY: THE TUNNEL SEALING EXPERIMENT (1998-2004)

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ABSTRACT

The Tunnel Sealing Experiment (TSX) was a test of a full-scale simulation of two independent tunnel bulkheads installed at Atomic Energy of Canada's Underground Research Laboratory (URL). One bulkhead consisted of a single mass pour of low-heat, high-performance concrete into a tunnel segment that had been keyed. The second was an assembly of highly compacted bentonite-sand blocks filling a second keyed segment of the same tunnel. The clay bulkhead was 2.8-m-long, 3.5-m-high and 4.2-m-wide. The keyed portion was 1m in depth and 2 m in length. The resulting bulkhead was approximately 60 m^3 in volume. An 11-m-long section of tunnel between these two plugs was filled with sand, flooded with water and pressurized. Following pressurization to 4 MPa, the water in the central region was heated and the influence of temperature on the tunnel plugs and the surrounding rock mass was monitored. Once clay bulkhead saturation was achieved, seepage past the clay bulkhead was Darcian and corresponded to an average hydraulic conductivity of approximately 10^{-11} m/s, regardless of temperature.

End-of-test sampling identified considerable volume changes in the upstream portions of the clay bulkhead, associated with early consolidation of the block assembly under the applied hydraulic heads. The ability of the clay bulkhead to accommodate substantial movement and volume change in its upstream regions demonstrates the importance of using sealing materials having sufficiently high plasticity and swelling capacity to accommodate deformation. The TSX, with its extensive monitoring system, its well-defined initial state and carefully measured end-of-test conditions, has provided a valuable set of data on the performance and evolution of a bentonite-based tunnel seal.

I. BACKGROUND

Bulkheads at the entrances to backfilled emplacement rooms play an integral role in ensuring the overall safety of a repository and so their performance must be demonstrated before they can be constructed in an actual repository. These seals provide restraint for the swelling clay materials that are incorporated within the room backfills as well as isolating backfilled and closed emplacement rooms from access galleries that may remain open during the preclosure phase of the repository.[1] The sealing and backfilling system within an emplacement room must minimize seepage, and hence the potential for advective transport of radionuclides, along the length of the tunnel. The keyed seal serves to interrupt flowpaths through the near-field rock, or the backfilled tunnels, and the low-permeability bulkhead provides sealing capacity in addition to that provided by backfill alone.

The TSX was designed to characterize the sealing potential of well-constructed, full-scale bulkheads from the perspectives of both engineering performance and safety assessment. It operated between 1998 and 2004 as a partnership between Agence nationale pour la gestion des déchets radioactifs (ANDRA), the Japan Nuclear Cycle Development Institute (JNC) and Atomic Energy of Canada Limited (AECL). During the isothermal phase of the TSX, the US DoE (via the Waste Isolation Pilot Project (WIPP)) was also a partner. One bulkhead was composed of highly compacted sand-bentonite blocks and the other was constructed using Low-Heat High-Performance Concrete (LHHPC)[1] as shown in Figure 1. The region between the bulkheads was filled with sand, flooded with water and then pressurized to 4 MPa. Ultimately the water within the sand-filled tunnel was circulated through two 30 kW heaters and the temperature of the sealing system was gradually increased, reaching a peak of 60^{o}C on the upstream face of the clay bulkhead.

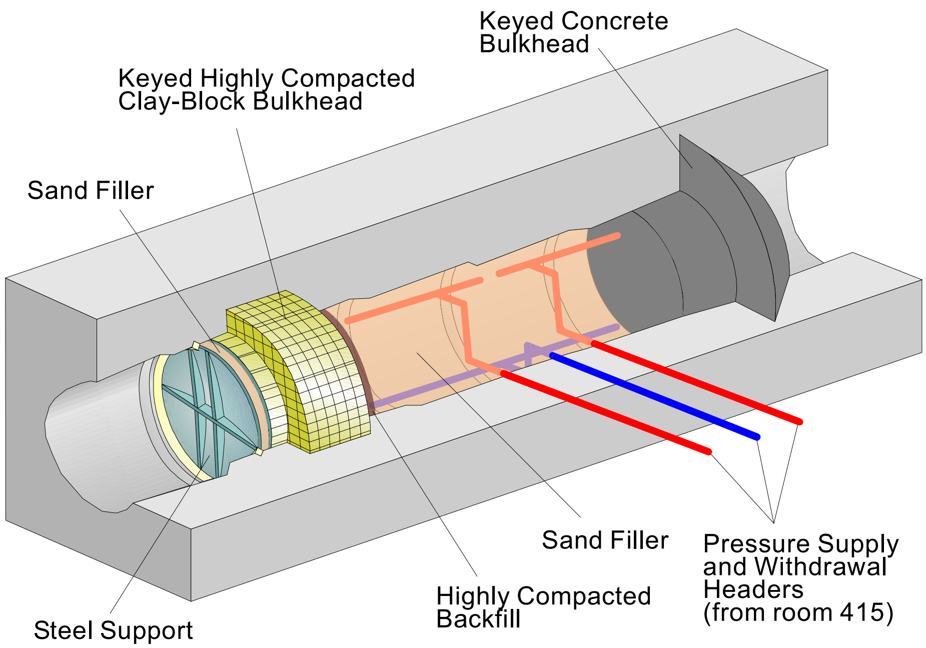


Figure 1: Layout of the Tunnel Sealing Experiment.

The primary objectives of the TSX were: to assess the applicability of various technologies for construction of practicable concrete and bentonite bulkheads; to evaluate the performance of each bulkhead; and to identify and document the parameters that affect that performance. In that context, performance of each of the TSX bulkheads was evaluated based on their ability to restrict water movement in the axial direction of the tunnel. In a repository, however, the ability of a seal to limit the transport of radionuclides is of greater importance than simply limiting the flow of water.[2] In order to evaluate this aspect of bulkhead performance, several tracer solutions were injected into the water supply at various times during the TSX's operation in order to aide in determining relevant transport properties of the bulkhead-rock sealing system. Information gained from this experiment can be used to set performance criteria for seals for safety assessment analyses of repositories. The end product of the experiment is information that can be used in engineering design and safety assessment of sealing systems for radioactive waste repositories. This paper discusses the performance of the clay bulkhead portion of the TSX. Discussion of the concrete bulkhead has been provided in other publications.[1,3,4,5]

II. CLAY BULKHEAD DESIGN AND CONSTRUCTION

In order to effectively cut off physical connections between the excavation damaged zone (EDZ) on the upstream and downstream ends of the clay bulkhead portion of the TSX, a key of 2-m length was mechanically excavated to a depth of 1 m beyond the perimeter of the original tunnel. This depth was selected as the result of predictions based on previous drill and blast excavations through the type of rock and under the stress conditions that were present in the TSX tunnel. Those results indicated that the EDZ would not extend beyond 0.5 m around the tunnel.[1] In order to physically interrupt this region and minimize the generation of further damage during key excavation, a depth of 1 m was selected for the key. It was excavated using line-drilling and hydraulic rock splitters.

As can be seen in Figure 2a, the excavated surface of the rock was rough in the vicinity of the clay bulkhead, and to provide a smooth contact with the clay blocks as well as to minimize any construction voids, a shotclay material was applied to this surface. The shotclay material was fabricated by first air-drying and crushing compacted clay blocks into particles of 10-mm diameter or smaller. This material was then pneumatically sprayed into place using conventional shotcrete equipment as shown in Figure 2b.

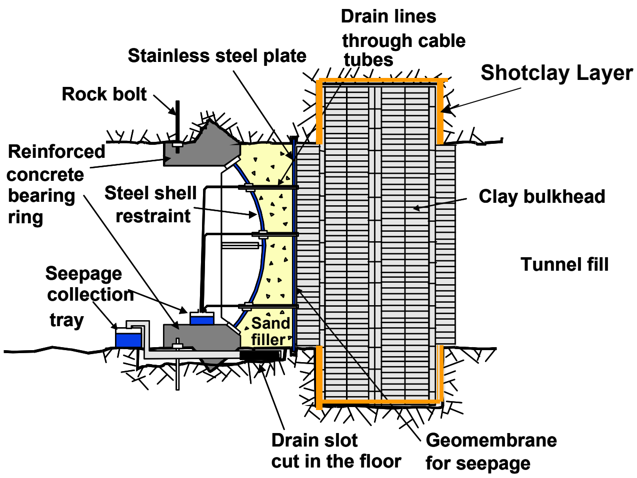
(a) Excavated Key for Clay Bulkhead

(b) Shotclay Application To Surface of Key

Figure 2: Clay key showing: (a) rough surfaces and (b) application of shotclay.

In order for the clay to generate swelling pressure upon saturation, the material must be constrained against volume expansion. The blocks installed in the clay bulkhead had nominal dimensions of 0.1 m by 0.36 m by 0.17 m and were arranged and installed in a manner that was intended to minimize the potential for straight planar flow along block interfaces (Figure 3a). Approximately 9000 blocks were used in the construction of the bulkhead. The target minimum dry density for the material was 1.9 Mg/m^3 and this was achieved. At this density the swelling pressure exerted by water-saturated bentonite would be about 1 MPa, and the hydraulic conductivity of the main part of the clay bulkhead was expected to be about 10^{-12} m/s.[6]

Physical constraint of the clay bulkhead in the downstream direction was provided by a very stiff steel and concrete restraint system (Figure 3). This restraint system was designed to resist the combined loading of 4 MPa of hydraulic pressure and 1 MPa of swelling pressure. The restraint system was essentially an elongated hemispherical steel shell, with a minimum plate thickness of 25 mm that transferred the load outward onto a high strength concrete bearing pad. The concrete bearing pad, in turn, was recessed into the rock and secured to its surface by rock bolts. A stainless steel plate and sand fill was used to transfer the load uniformly from the clay bulkhead to the steel shell.[1]



(3a) Block Layout Schematic

(3b) As-placed Blocks

Figure 3: Clay bulkhead construction.

A predominantly sand material, representative of densely compacted tunnel backfill, was placed immediately adjacent to the upstream (pressure chamber) face of the clay block assembly. The backfill material contained 10% bentonite by mass, and was compacted to high density, in order to provide resistance to the swelling of the clay blocks. Also, the inclusion of the clay in the backfill inhibits the extrusion of the bentonite from the bulkhead into the sand. The backfill material of 10% bentonite and 90% sand was placed as a 0.3 m wide wall adjacent to the clay blocks using a combination of *in situ* dynamic compaction in the lower two-thirds of the tunnel and pneumatic placement in the upper third. The sand fill occupying the region between the bulkheads was compacted in 150 mm lifts using a vibratory plate compactor. In the top third of the excavation, where there was insufficient room for the compactor to be used, the sand was placed pneumatically.

III. CLAY BULKHEAD BEHAVIOUR DURING TSX OPERATION

Originally the water-saturated sand chamber was to be pressurized in a continuous stepwise manner until the full operating pressure was reached. However a number of factors led to changes in this plan. Firstly, but not unexpectedly as hydraulic head was increased, an unacceptably high seepage rate past the concrete bulkhead developed along its interface with the surrounding rock mass or via the disturbed rock. This was addressed by cement grouting of the interface using pre-installed grouting tubes after which pressurization of the TSX was resumed. The second and more significant impediment to early TSX pressurization was a series of eight flow events that occurred through the clay bulkhead during the first 7 months of TSX operation (1998 October – 1999 April). The largest involved 20,000 litres of water flowing from the pressure chamber into and through the clay bulkhead, or along the interface between the shotclay and rock.[6,7,8] These events resulted in partial or complete loss of hydraulic head within the pressurized portion of the tunnel and necessitated a period of rest under reduced hydraulic head before pressurization could be resumed. These periods of rest allowed the shotclay and clay within the bulkhead time to swell and close the flow-paths that had been generated. These flow events highlighted the importance of using a composite seal in an actual repository as components such as concrete could assist in limiting flow until the bentonite-based materials were able to swell and seal any joints or gaps left following bulkhead construction.

Observations made via the seepage collection system installed at the downstream face of the clay bulkhead, small transient temperature changes and readings from the total pressure cells all indicated that the large-flow events were occurring along the interfaces between the shotclay and the adjacent rock and clay block materials. To a lesser extent these events apparently moved quantities of water into the core regions of the clay bulkhead via pre-existing joints between clay blocks. While initially disconcerting, these flow events actually worked to some advantage by speeding the hydration process of the clay bulkhead. Figure 4 shows the pattern of water uptake within the clay bulkhead. A total of 132 thermocouple psychrometers (PSY), 14 hygrometers (HYG) and 12 time domain reflectometers (TDRs) were installed throughout the clay bulkhead in order to monitor the manner in which the clay bulkhead took on water. Each of these sensor types measured water content in a different manner but their readings were converted to suction to provide common measurement units. As water content increases the total suction decreases and so patterns of decreasing suction are indicative of a system that is moving towards saturation.

The blue shading in Figure 4 shows how the clay bulkhead first took on water in the perimeter regions, with more gradual saturation of the core. Figure 4 also shows an early hydration at the mid location of the bulkhead (1.2 m) that corresponds with the protruding blocks at mid bulkhead shown in Figure 3. By 1999 March the large flow events had concluded and the clay bulkhead had begun to wet from the perimeter (shotclay) regions and the upstream face (2.3 m) in a downstream direction and towards the core of the bulkhead. The impact of the narrow region of shotclay on bulkhead hydration was substantial and appears to have dominated the saturation process. After the year 2000, sensors indicated that the clay bulkhead, with the exception of a small region in the lower, downstream area had reached saturation.[6,7]

The nature of water content sensors does not allow them to indicate whether there was a density change associated with the soil during water uptake or following saturation. Confirmation of the saturation-state and determination of what density changes had occurred during the course of the TSX's operation was obtained through extensive physical sampling conducted at the time of decommissioning.[8]

Table 1 summarizes the as-placed and end-of-test conditions for the clay bulkhead materials. The dry density and gravimetric water content of the clay blocks used in TSX construction were approximately 1.93 Mg/m^3 and 14.7% respectively. This material requires a gravimetric water content of approximately 15.1% to achieve saturation. The small gaps and joints present at the time of bulkhead construction resulted in a slight decrease in the average density and a corresponding increase in the saturated water content as shown in Table 1. The physically measured water contents present throughout the clay bulkhead provided a good indication of where localized or regional swelling (or compression) had occurred. When the gravimetric water content of recovered materials measured in excess of 15.1% then swelling must have occurred and likewise a gravimetric water content of less than this indicated that consolidation had occurred.

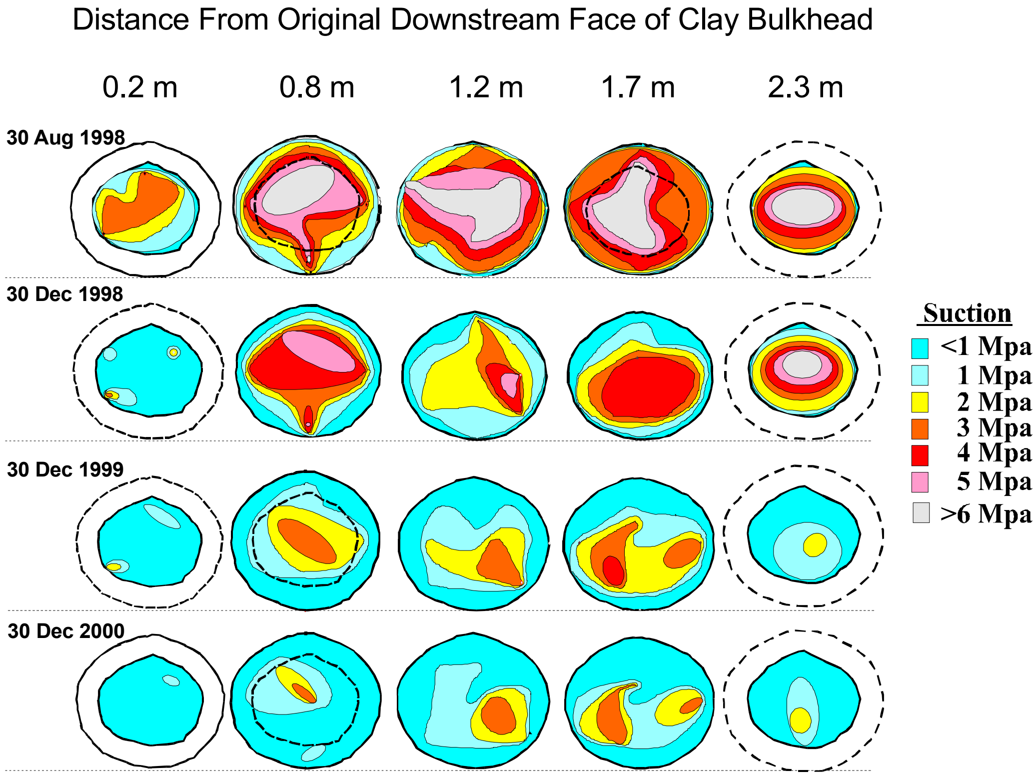


Figure 4: Water uptake by clay bulkhead as measured using psychrometers and hygrometers (relative humidity values converted to suction equivalents).

The shotclay materials placed in the region between the blocks and the rock had an estimated as-placed dry density of 1.3 Mg/m^3 and gravimetric water content of 18.5%.[1] Table 1 provides a summary of the water content and density conditions in this bulkhead component at the start of the TSX and at the time of decommissioning. Gravimetric water content higher and less than the approximately 37% required to achieve saturation in the as-placed materials are indicative of swelling and consolidation respectively.

A compilation of the decommissioning moisture content measurements collected along a series of vertical planes through the clay bulkhead is provided in Figure 5. The data show a system that was not at moisture or density equilibrium at the time of decommissioning. The most dramatic feature in Figure 5 is the presence of a region of high water content (lower density) along the outer perimeter of the upstream end of the clay bulkhead and along the upstream face of the keyed portion of the tunnel (at ~2.2 m and ~2.4 m from the downstream end of clay bulkhead). This corresponds to a region where low-density (<1.35 Mg/m^3) materials were present at the time of decommissioning and is indicative of a region where gaps may have been present at some time during TSX operation (a conclusion supported by displacement sensors installed in the bulkhead[6]). The upstream face of the clay bulkhead moved approximately 53 mm in the downstream direction during pressurization of the water in the tunnel portion of the TSX (Figure 6). This type of deformation was most likely the result of physical compression of the bulkhead due to closing of gaps and joints left from construction. This compression would have resulted in the opening of a gap along the shotclay/block/rock contact at the upstream face of the block-occupied key. These materials would have to swell in order to maintain/recover their contact with the rock. Such swelling would have resulted in a reduction of the density of the sealing material in this region at least over the short to intermediate term. Water contents in the upstream face of the keyed portion would therefore exceed ~37%, the value for the as-placed shotclay at saturation. Swelling was observed in the regions immediately adjacent to the upstream face of the keyed portion of the clay bulkhead where water contents as high as 60% were measured locally during decommissioning. It should be noted that reduction in the density of material at the upstream end of the clay bulkhead was only discernible for about 100 mm into the clay bulkhead.

Table 1. Water Content, Density and Saturation State of Clay Bulkhead Components

Material	Water Content (%)	Dry Density (mg/m^3)	Degree of Saturation (%)	Saturated Water Content (%)
Shotclay				
As-Placed*	~18.5	~1.3	~46	~37.3
EoT @ downstream face of Key	~18	~1.8	100	~18
EoT @ upstream face of Key**	30-60	1.0-1.5	100	30-60
Clay Blocks				
Initial Blocks	14.7±0.3	1.93±0.02	>95	15.1
Blocks-Bulkhead EoT***	13-17	1.86-2.01	100	14-16
Backfill-As-Placed				
Lower Portion (dynamic)	5	2.1	50	10
Upper Portion (pneumatic)	14	1.85	85	16.5
Backfill-EoT				
Lower Portion (dynamic)	8.5±0.7	~2.2±0.1	100	8.5
Upper Portion (pneumatic)†	14-28	1.5-1.9	100	14-28

* The shotclay material was recognized to be variable in its as-placed density and these data are estimates only.
** Shotclay on the upstream face was very wet and no clear boundary existed between the shotclay and blocks.
*** Clay blocks at least 0.15m distance from the clay-rock contacts, wettest materials at upstream end of bulkhead.
† A strong density gradation existed in this region with least dense materials at upper contact with rock.
EOT = End-of-Test

Less dramatic but still evident in Figure 5, is the change in the water content of the shotclay on the downstream face of the keyed region. The shotclay material in this region was clearly compressed from its as-placed condition, having an average dry density in the order of 1.8 Mg/m^3. There was also some slight compression of the block material at the downstream end of the clay bulkhead. Both of these materials were subject to hydraulically-induced compression throughout the course of the TSX, resulting in consolidation of less dense materials at the downstream end of the clay bulkhead. Figures 7 and 8 present some of the hydraulic and total pressure cell data collected. A comparison of these two figures highlights the importance of using different types of sensors. The total pressure cells are unable to separate out the proportions of the total pressure that is the result of swelling pressure, hydraulic pressure and hydraulically-induced mechanical pressure within the clay bulkhead. The hydraulically-induced "mechanical" compression of the system on the downstream face is a result of the very low hydraulic conductivity of the clay bulkhead and the free-drainage at the downstream face. This resulted in the hydraulic pressure in the pressure chamber acting more as a consolidating mechanical force on the downstream end of the clay bulkhead than as a porewater pressure (as reflected by the porewater pressures recorded within the clay bulkhead in Figure 8). The result of this "mechanical" compression was a very-tight contact between the clay and the rock at the downstream face of the key as evidenced by the high total pressures measured both radially and axially in the downstream regions of the bulkhead (Figure 7).

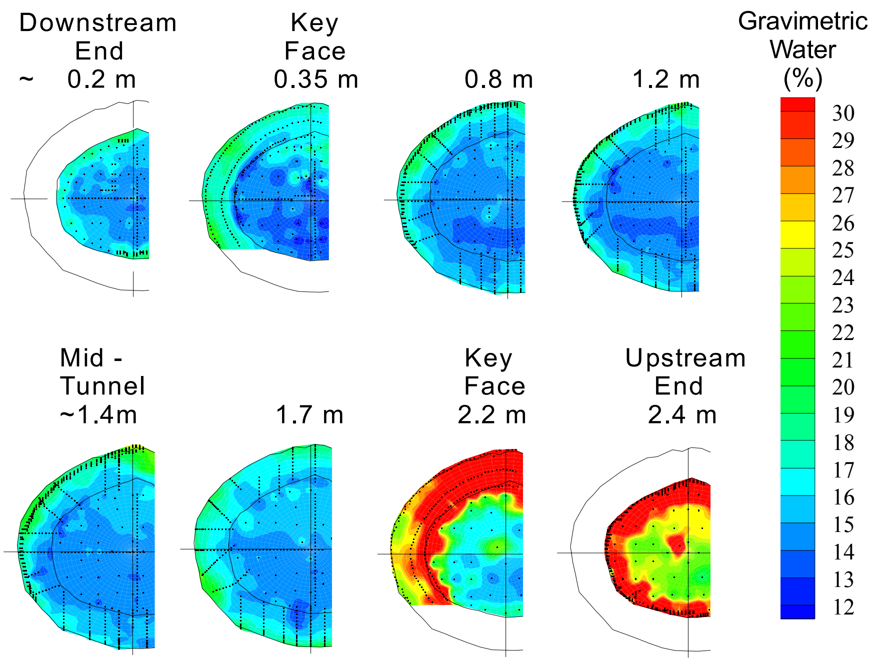


Figure 5: End-of-test moisture content profiles through the clay bulkhead.

The effectiveness of a clay bulkhead in a repository environment is measured by its ability to retard the movement of contaminants axially along the tunnel. In the TSX this was assessed in two manners, one being the physical measurement of water seepage past the bulkhead and identification of the regions where this seepage occurred. Tracer tests to determine travel times through the bulkhead were also conducted in the course of the TSX. The results of these tracer tests are presented elsewhere.[5]

The stainless-steel plate on the downstream face of the clay bulkhead (Figure 3) had 18 separate seepage collection zones installed on it and these were monitored to determine the pattern and quantities of seepage [1,6,7] Figure 9 presents the record of the total seepage past the clay bulkhead once the large-flow events (1999 January-June), had ceased and the self-sealing had taken place. Water seepage past the clay bulkhead was monitored regularly and the rate observed was directly proportional to the hydraulic gradient across the bulkhead (i.e., Darcian) as shown in Figure 9. Seepage past the clay bulkhead was determined to be dominated by the perimeter regions of the bulkhead (the shotclay) which transmitted >95% of the seepage collected. The average rate of water seepage past the clay bulkhead was calculated to be equivalent to 10^{-11} m/s. Changes in the temperature induced by heating of the chamber portion of the TSX did not noticeably affect the rate of seepage.

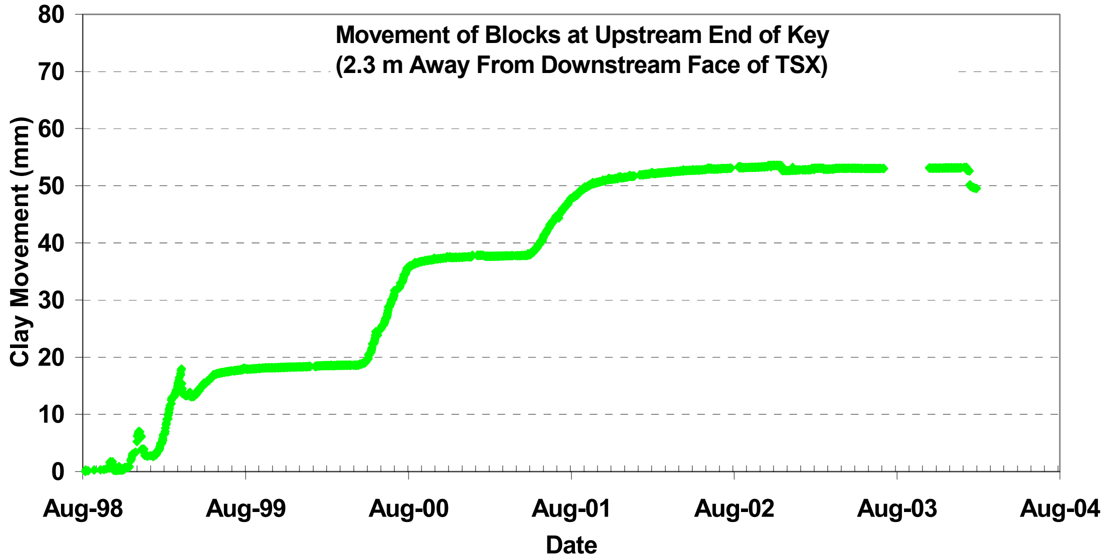


Figure 6: Physical deformation of clay bulkhead during TSX operation.

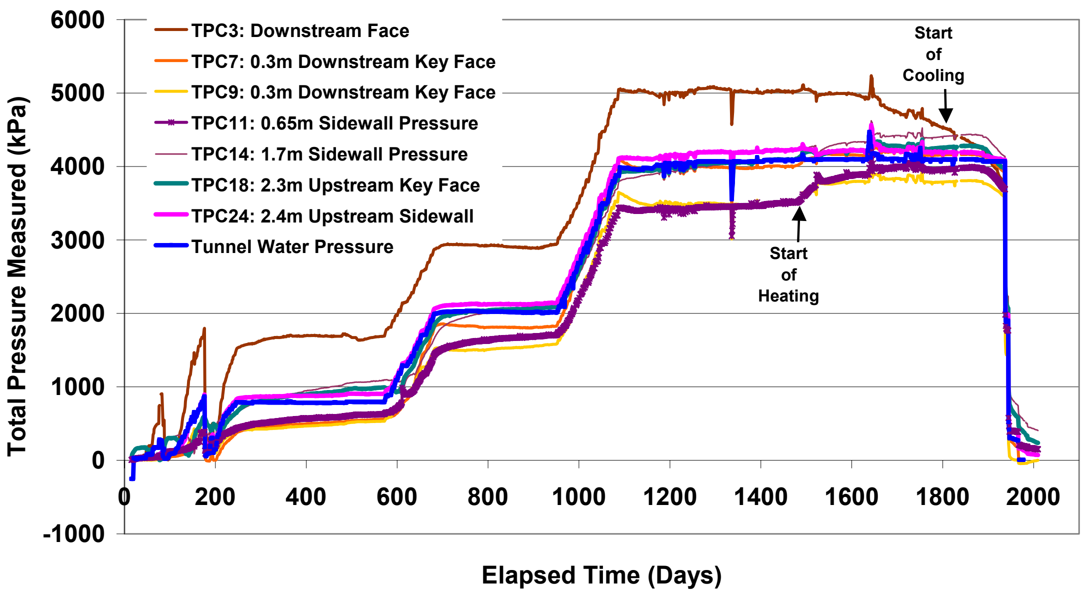


Figure 7: Total pressures at rock-clay contacts in TSX.

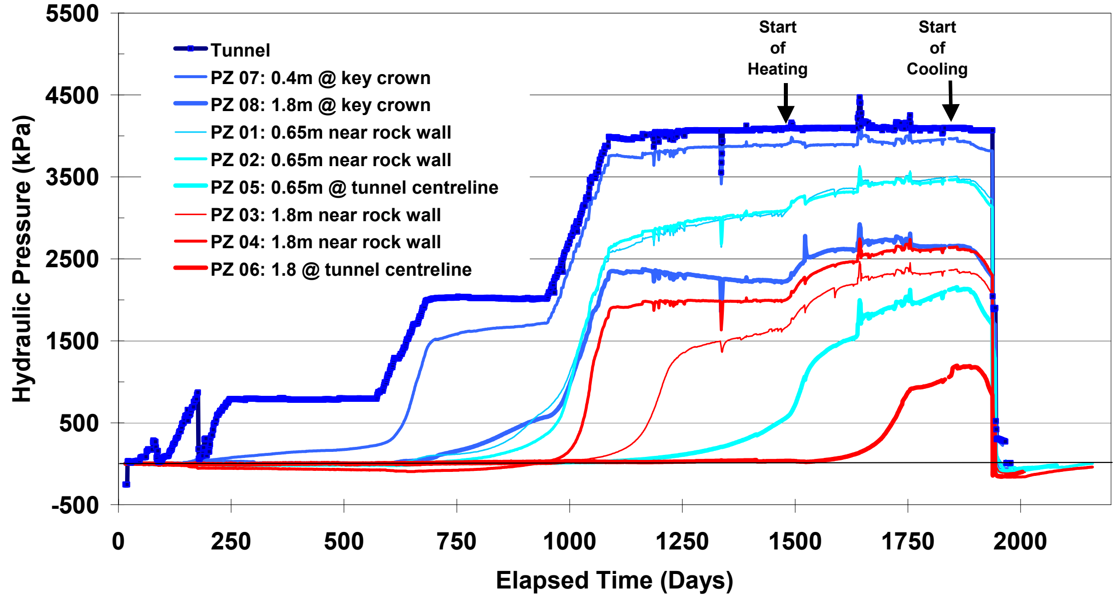
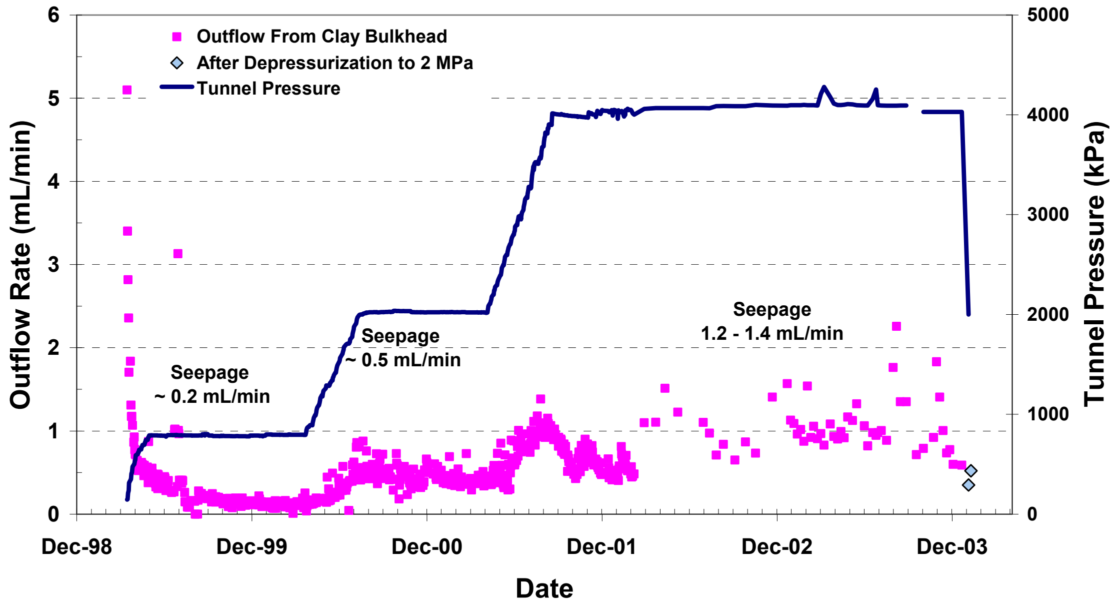


Figure 8: Piezometric pressures observed within clay bulkhead.



(Note: distances are measured from upstream face of clay bulkhead)

Figure 9: Seepage of water past the clay bulkhead portion of the TSX.

IV. SUMMARY

This paper has presented some of the observations made in the course of conducting the TSX at AECL's URL. The clay bulkhead provided an effective barrier to water transport, limiting average flow to approximately 10^{-11} m/s, demonstrating the effectiveness of a clay-filled key in cutting off flow along the axis of a full-scale tunnel within an intact highly-stressed rock mass. The interface between sealing materials and the rock has been shown to be critical in controlling mass transport as this is the most hydraulically conductive region, at least in the early stages of repository evolution.

The large flow events that occurred early in the TSX highlighted the importance of keeping joints and interfaces to a minimum and also demonstrated the ability of a carefully constructed clay bulkhead to close off existing flow paths and to self-seal. The importance of the restraint system to physically support high loads and provide resistance to water flow was also demonstrated. The downstream face of the clay bulkhead was subjected to the sum of the swelling pressure and the hydraulic head and this could be expected to occur in a repository that is open for an extended period while emplacement operations continue. A bulkhead isolating a room must be able to withstand mechanical loads while retarding water flow through it during its initial hydration in order to minimize seepage. It should be noted that an emplacement room is unlikely to provide an essentially unlimited source of free-flowing water such as occurred in the sand-filled TSX. It is expected that an emplacement room would be backfilled using a low-permeability material that would preclude such large-flow events from occurring.

The TSX has provided an engineering demonstration of construction of components that will be necessary in a deep geologic repository as well as identifying and assessing the thermal, hydrologic, mechanical, chemical and biological processes that would be active in a repository environment.

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