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THE TUNNEL SEALING EXPERIMENT: A REVIEW

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ABSTRACT

The Tunnel Sealing Experiment (TSX), a major international experiment, demonstrating technologies for tunnel sealing at *in situ* full-scale, was conducted at Atomic Energy of Canada Limited's Underground Research Laboratory (URL). The objective of the experiment was to demonstrate technologies for construction of bentonite and concrete bulkheads, to quantify the performance of each bulkhead and to document the factors that affect the performance. It was not the purpose of the experiment to demonstrate an optimized bulkhead. Two bulkheads, one composed of low heat high performance concrete and the other of highly compacted sand-bentonite material, were constructed in a tunnel in unfractured granitic rock at the URL. The chamber between the two bulkheads was pressurized with water to 4 MPa in a series of steps over a two-year period. The ultimate pressure is representative of the ambient pore pressures in the rock at a depth of 420 m. The first phase of the TSX was conducted at ambient temperature (15°C) while a second phase involved heating the pressurized water between the bulkheads and the temperatures ultimately reached 65°C at thermistors near the upstream face of both bulkheads. Instrumentation in the experiment monitored parameters that are important indicators for bulkhead performance. Seepage was measured at both bulkheads and any other leakage points from the tunnel to maintain a water balance. The paper provides an overview of the project.

I. INTRODUCTION

Concepts for deep geologic disposal of radioactive waste, as advanced by many international organizations, include bulkheads or plugs in access shafts and ramps, or at the entrances to disposal rooms, or both. The safety of the respective disposal systems relies on the combined performance of the natural barriers (host rock) and engineered barriers (the waste form, the waste container, the repository sealing systems). To understand the functionality of these systems it is important to study them in whole or in part at full scale. One such study was the Tunnel Sealing Experiment (TSX), an *in situ*, full-scale tunnel seal component study.

The TSX has two seals (Figure 1). One was made of low heat high performance concrete (LHHPC) developed at Atomic Energy of Canada Limited (AECL)[1] and the second was made of approximately 9000 highly compacted sand bentonite material blocks (dry density ~1.9 Mg/m^3). The swelling of the clay bulkhead was confined by sand in the test chamber on one side and by a structural steel restraint on the other. In the first phase of the TSX the central 12-m-long sand-filled test chamber was pressurized to 4 MPa by means of a static water head. A circulation pump and heaters were added for a second thermal phase that involved heating the water in two steps to increase the temperature at the upstream face of each bulkhead to 65°C. At the conclusion of heating, a three-month cooling period was followed by depressurization of the tunnel. Samples were then taken to measure the post-test conditions in terms of density, water content, structure, chemistry and strength. The first phase of the TSX was conducted jointly at the URL by Japan Nuclear Cycle Development Institute (JNC), Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA) of France, the United States Department of Energy (through the science advisor for Waste Isolation Pilot Plant) and AECL to investigate technologies for construction of repository seals and the performance of those seals. The second phase was conducted by JNC, ANDRA and AECL.

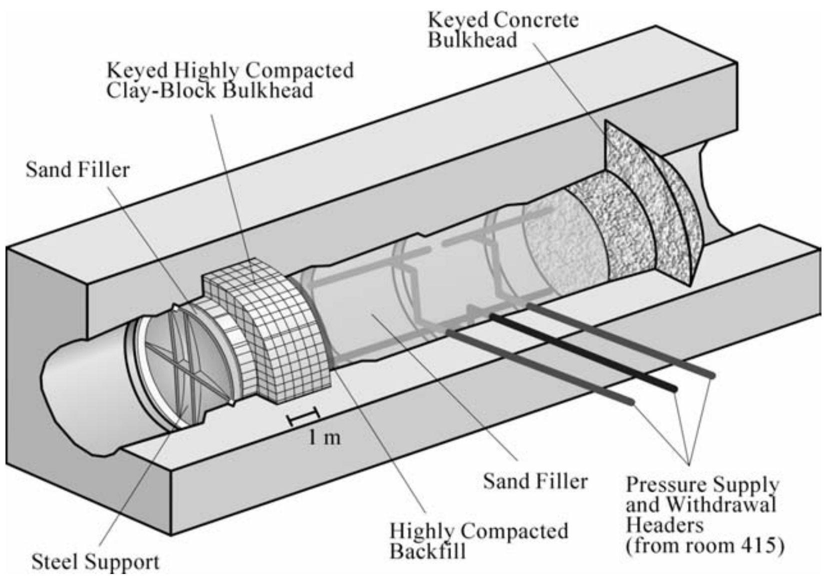

Figure 1: Configuration of the TSX, Clay Bulkhead is a total of 2.6 m thick; Concrete Bulkhead is 3.5 m thick.

II. CONSTRUCTION

The construction of the TSX required a multidisciplinary approach and a concerted effort to bring the project to the operational phase. The first step involved tunnel design and layout. The tunnel shape was a compromise between the best geometry for the *in situ* stresses (σ_1 = 60 MPa (trend/plunge 145.0°/14.6°), σ_2 = 48 MPa (53.5°/5.8°) and σ_3 = 11 MPa (302.6°/74.2°) and practical tunnel shape for construction purposes. The tunnel was excavated parallel to the trend of the maximum principal stress, had a 3.5-m-high by 4.375-m-wide elliptical cross section and was 40 m in length. After performing a study of the excavation damage zone (EDZ) surrounding the tunnel, it was determined that in order to minimize axial flow, the bulkheads should be keyed into the tunnel perimeter. Numerical analysis indicated that if the keys could be excavated into the rock with a minimum of new damage then the keys should act to interrupt flow through the EDZ[2].

The TSX tunnel was excavated by full face drilling and blasting, but the keys were excavated using a rock excavation technique called perimeter line drilling and rock splitting. Holes were percussion drilled to delineate a section of rock. The holes were then reamed to a larger diameter so they overlapped, thus isolating the rock section. Further holes were drilled into this isolated plug and a hydraulic rock splitter was used to induce tension in the rock causing cracking. The rock splitting process was repeated until the entire rock section was broken out with a minimum of new damage. Numerical modelling indicated that a combination of a sharp angled and a vertical face in the keys to be the best for interrupting the EDZ. This wedge shape was selected for the concrete key (Figure 1). A rectangular shape was selected for the clay key to aid in placement of the rectangular-shaped pre-compacted clay blocks. Excavation of the tunnel took approximately 416 working hours, while the clay and concrete keys took 592 and 776 working hours to excavate respectively.

During construction, time was allotted for experimental activities including measurements of hydraulic conductivity and determination of the extent of damage surrounding the tunnel. In parallel, a trial clay block placement was conducted in a test excavation and large number of boreholes were drilled for instrumentation, water delivery and cabling[2]. The installation of the seals began from the clay bulkhead side and proceeded towards the concrete bulkhead. The pressurization system was installed in parallel with the seal construction. It supplied pressurized water by means of a standing water head; a pressure-reducing valve permitted the water pressure in the tunnel to be increased as desired. It was designed to allow the thermal circulation loop to be added for the second phase of the TSX.

In order to resist the combined loading of 4 MPa of hydraulic pressure and 1 MPa of swelling pressure from the clay bulkhead, a rigid steel restraint system (Figures 1 and 2) was installed first. 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 reinforced 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.

The clay bulkhead was installed following construction of the steel restraint system. The clay bulkhead material (70% Kunigel V1 bentonite clay and 30% graded silica sand) was compacted into blocks with nominal dimensions of 0.1 m x 0.36 m x 0.20 m. The blocks were fabricated using a modified adobe brick maker. The minimum target dry density for the material was 1.9 Mg/m^3. Blocks that did not meet quality control specifications were discarded before installation. Any gaps between the blocks were filled with discarded block material crushed and hand-screened to sizes less than 2 mm. The size of blocks facilitated hand placement and permitted the placement of 235 instruments and their leads, and prevented damage to the instrumentation that could have resulted from *in situ* compaction of the clay. The use of small blocks and the need to carefully install instrumentation increased construction time. In order to better seal the clay rock interface, shot clay material was applied to the rock surface. The shot clay material was fabricated by first air-drying and crushing compacted clay blocks into particles of 10-mm-diameter or smaller, and then returning the material to the mixing machine to “round” off the corners of the particles. This material was then pneumatically sprayed into place using conventional shotcrete equipment. The operator added water to the shot-clay at the nozzle of the sprayer to produce a material that would stick to the walls and have consistent and relatively compact characteristics. The applied dry density was approximately 1.3 Mg/m^3 at a moisture content of 22%. The thickness of the shot-clay layer varied from 5 to 60 mm depending upon the roughness of the rock surface. The shot-clay was applied pneumatically at a rate of approximately 100 kg/min. The total volume of material in the clay bulkhead was 67 m^3. As the clay bulkhead was being constructed, a 0.3 m sand-clay backfill wall was built on the test chamber side of the tunnel to serve as both support and erosion control for the clay bulkhead. The lower two thirds of the backfill were compacted with a pneumatic hammer, while the upper third was pneumatically placed after completion of the clay bulkhead. At this time instrumentation in the chamber and the remainder of the pressurization system were installed.

Sand was installed in the chamber between the clay bulkhead and the concrete bulkhead. The lower portion was placed by an underground loader and compacted using a vibratory plate compactor. The upper portion was pneumatically placed and not compacted. Sand was chosen to allow movement of water inside the tunnel, while providing resistance against expansion of the clay bulkhead and reducing the water volume required to fill the tunnel. During decommissioning it was found that the sand had settled and a gap of up to 30 mm at the top of the tunnel crown had opened. Due to the presence of clay up to 0.5 m into the gap it appears that at least part of the gap existed during the operation of the experiment. However, microseismic sensors in the rock around the tunnel showed no damage occurring along the roof during pressurization and heating. This suggests that the water pressure in the tunnel may have provided sufficient confining pressure to prevent rock damage from occurring in the tunnel roof. The confining pressure provided by the sand and other materials in the lower part of the tunnel inhibited rock damage in that region.

A 250-mm-thick wall was cast to provide an inner form against which the concrete bulkhead could be poured and to act as a buttress for the remaining sand placement. The concrete wall and bulkhead (Figure 2) were composed of LHHPC. In LHHPC a substantial part of the Portland cement is substituted with pozzolanic silica fume and non-pozzolanic silica flour and a naphthalene-based superplasticizer is used to enhance workability. These substitutions lower the heat of hydration and also reduce the pH of the cured concrete to less than 10. The cement, silica fume and silica flour were blended, batched and bagged for use in pre-weighed quantities. The dry aggregates were similarly and separately prepared. Both the fine and coarse aggregates were derived from a glacial deposit and were mostly of granitic origin.

The front form of the concrete bulkhead was timber and steel with a geotextile lining to allow water to be supplied to the front face of the bulkhead. No structural reinforcement of the concrete bulkhead was required, however, a glass fibre rod framework was installed on which instruments and their cables were mounted. A total of 130 sensors were cast within the bulkhead to monitor deformation, temperatures, porewater suction (during curing only), interface displacements, and acoustic emissions and velocities. The acoustic events are small-scale energy releases associated with microcrack development. Grouting tubes were installed prior to pouring to permit later grouting of the concrete-rock interface.

The concrete was mixed in 1.6 m^3 batches in a static drum, rotating blade mixer, having a maximum capacity of 2 m^3. The mixer was located within the surface facilities of the URL, and the concrete was discharged directly into a rail car, which was used to transport the material underground via the shaft hoist. Underground, the contents of the rail car were emptied into a pump, which delivered the concrete the last 10 m horizontally to the concrete bulkhead. The volume of the concrete bulkhead was 76 m^3 and the entire pour was completed in less than eight hours.

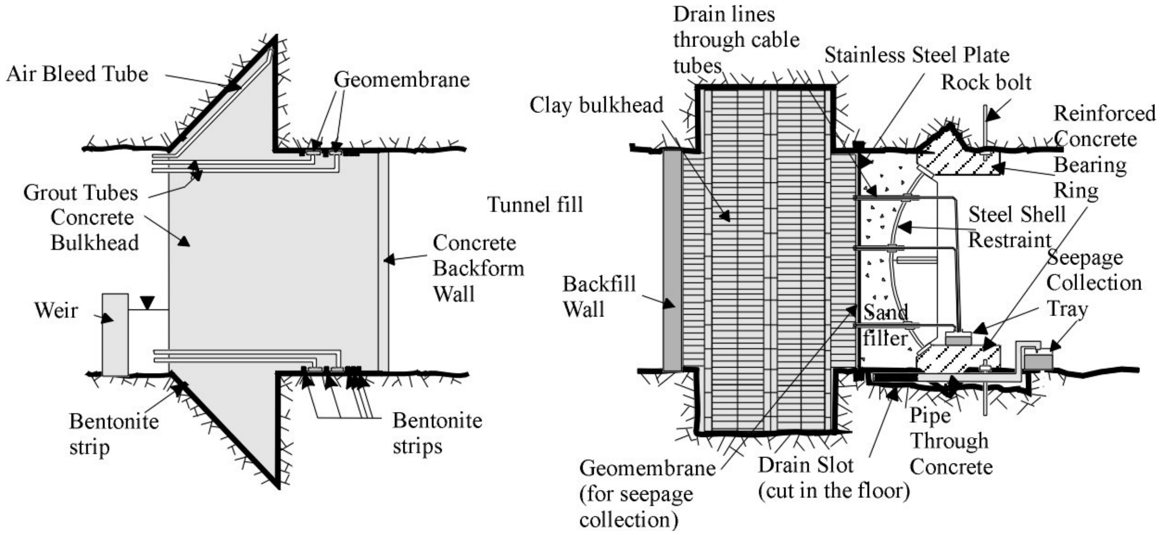

Figure 2: Clay Bulkhead and Restraint and Concrete Bulkhead.

III. OPERATION

The operation of the TSX began in 1998 September with the initial flooding of the chamber between the bulkheads. The pressurization sequence was originally designed to reach 4 MPa in 4 months. Initial seepage past the concrete bulkhead at pressure of 35 kPa was 500 mL/min and hydration of butyl-bentonite strips installed on the rock-concrete interface was reducing the flow with time. Tunnel pressure was slowly increased until it had reached 300 kPa at which time seepage past the concrete had increased to 1.6 L/min[2]. This equated to an interface transmissivity of 10^{-7} m/s. It would not have been possible to operate the TSX at full pressure without reducing the leakage along the interface, so pressure was reduced and grouting was conducted using pre-installed tubes connected to geomembranes for grout distribution at the interface. Grouting reduced the measured seepage by three orders of magnitude.

The pressure in the chamber was again increased following completion of grouting but a series of eight flow events occurred at the clay bulkhead, the largest involved 20 m^3 of water at 270 kPa but most were less than 1 m^3[3]. Observation of the tunnel floor after removal of the leakage water showed that no discernable amount of clay had been washed from the bulkhead, although during decommissioning, several seams of fine material were uncovered near the rock-clay interface. Several ‘pipes’ of coarse-only material were also found in the upper pneumatically emplaced portion of the backfill wall during decommissioning. Because of these flow events; the rate of pressure increase was slowed to permit gradual hydration and swelling of the clay to progress. The water pressure was raised stepwise to 800 kPa by 1999 May and subsequently held at 800 kPa until 2000 April. During that period a tracer test using sodium iodide and fluorescein was performed to allow evaluation of the solute transport characteristics of the two seals. The tracer tests allowed the travel time past the seals to be determined. Pressure was increased to 2 MPa by 2000 July and was again held constant until 2001 March when it was gradually increased to 4 MPa by 2001 August. This was 19 months of pressurization, not including the stable monitoring periods. During the period at 4 MPa, a second tracer test using sodium bromide was conducted and the thermal loop of the pressurization system was installed. In 2002 September, the ambient temperature phase ended and heating began. Temperature on the upstream side of the bulkheads was first increased to nearly 50°C and then to approximately 65°C in a second heating step. A third (rhodamine) and fourth (sodium iodide) tracer test were conducted during heating. Heating was completed in 2003 November and was followed by a three-month cooling period prior to draining the tunnel and sampling in 2004.

Extensive samples were taken on one half of the clay bulkhead (the second half was not removed) to measure density, moisture content and to inspect for the presence of tracer. The concrete bulkhead was studied more selectively. In part this was done as it was more difficult to remove a sample of concrete and secondly because it was not anticipated that the concrete properties would vary significantly. Samples were taken at specific locations of interest to compare regions that had experienced different temperatures and exposures to water. Samples were taken for strength testing, chemistry and structure.

VI. SEEPAGE

The primary measure of bulkhead performance was seepage. The rock mass surrounding the TSX tunnel was unfractured and had low permeability. Prior to excavation of the bulkhead keys, a series of EDZ measurements and hydraulic conductivity measurements were made in the tunnel. Hydraulic conductivity was measured only in the TSX tunnel floor and was approximately 10^{-8} m/s, while the intact rock values are approximately 10^{-13} m/s. Seepage was monitored at potential leakage points, such as pressurization and cable boreholes as well as the bulkheads. Because different locations in the clay bulkhead were expected to reach saturation at different times, an eighteen-zone seepage monitoring system was installed on the stainless steel wall. While seepage was recorded at most zones early in the hydration process, the primary seepage pathway was through the lower density shotclay material at the clay bulkhead perimeter.

It was assumed that the primary pathway for seepage past the concrete bulkhead would be along the rock-concrete interface so no zonal monitoring system was installed to collect seepage through the concrete bulkhead. During pressurization, several discrete locations around the interface showed evidence of seepage. These locations included the crown, mid-height on the wall, and floor areas. At ambient temperature and 4 MPa hydraulic pressure the seepage past the concrete and clay bulkheads were 10 and 1 mL/min, respectively after approximately 1400 days of operation. This translated into an effective hydraulic conductivity for the clay and concrete tunnel seals of 8.6×10^{-12} m/s and 1×10^{-10} m/s, respectively. When the temperature was increased there was essentially no change in the seepage past the clay bulkhead but because of the expansion of the concrete with heating the seepage past the concrete bulkhead reduced to 1 mL/min, during cooling the seepage increased to approximately 2 mL/min. Figure 3 shows the seepage rates during the TSX for the concrete and clay bulkheads. It is important to note that these seepage conditions exist with a limitless water supply. Seepage would be much lower with a lower pressure differential or restricted water supply.

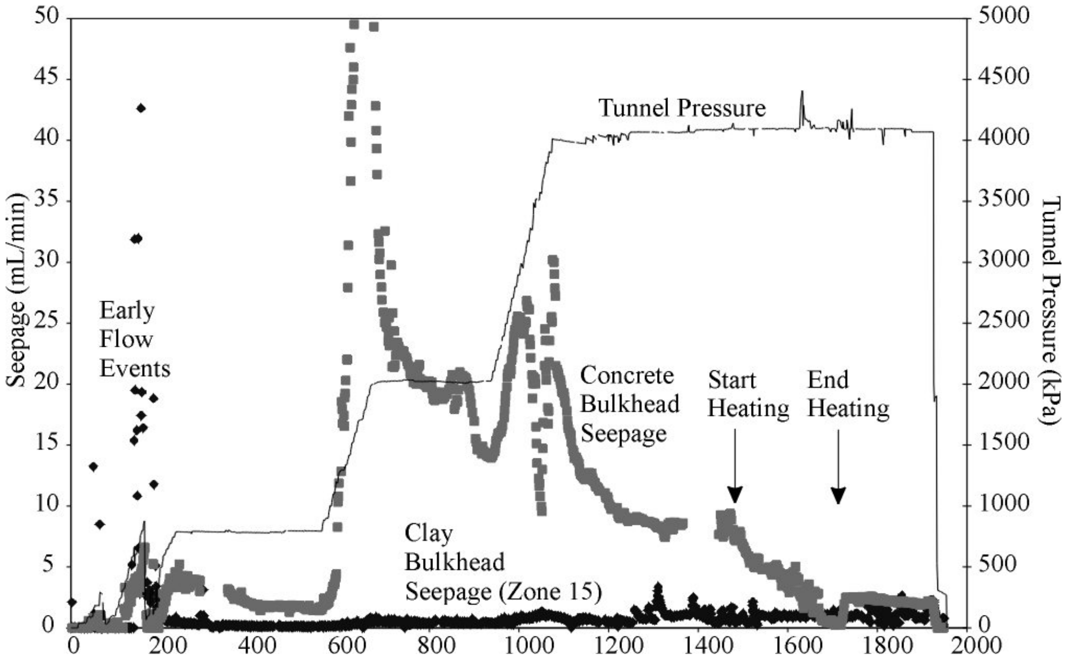

Figure 3: Clay and Concrete Bulkhead Seepage.

V. CLAY BULKHEAD RESPONSE

The early clay bulkhead response was a direct consequence of the methods of its construction and the conditions of the tunnel pressurization. The bulkhead was very carefully built but had thousands of individual interfaces, between adjacent blocks, between the blocks and the shotclay and between the shotclay and the rock. Each of these interfaces provided potential pathways for water flow. During the early phases of pressurization, water moved along some of these pathways and eight flow events occurred. After the tunnel pressure was raised above 800 kPa after nearly one year of hydration, no further flow events occurred due to closure of the interfaces by swelling of the clay. Moisture sensors installed in the bulkhead showed that the water during the flow events did not just leak past the bulkhead but entered the core as well[4]. Continued water movement during the TSX operation through the more permeable shotclay supplied water to the downstream end of the clay bulkhead. Thus the saturation pattern of the clay bulkhead was radial with saturation occurring from the upstream, downstream and perimeter towards the centre instead of only a front from the upstream to downstream side. The bulkhead core was nearly saturated by 1999 December with the exception of small regions of the centre. By 2001 December the bulkhead was fully saturated.

Piezometers and pressure cells were installed to monitor hydraulic, loading and swelling pressures in the bulkhead. The hydraulic pressures decreased with increasing distance from the upstream face and from the tunnel walls. Similarly the regions closer to the core of the bulkhead took longer to show any hydraulic pressure development. On reaching 4 MPa water pressure in the tunnel, piezometers in the clay bulkhead closest to the chamber were nearly 4 MPa while those near the core were still close to zero. Pressure slowly increased in these zones as pressure slowly moved towards equilibrium. During heating, piezometers in several regions showed rapid pressure increase and this was attributed to thermal expansion of the porewater and a restricted ability of this increased water volume to drain from the low permeability clay bulkhead. Upon cooling, these pore pressures showed a decrease due to thermal contraction.

Pressure cells were installed around and within the clay mass. They were arranged into roughly three arrays at 0.65, 0.95 and 1.85 m from the upstream face of the bulkhead. Those nearest the chamber showed the earliest pressure increase and were the most responsive to tunnel pressure changes. Pressure did not increase equally at all locations during early phases of pressurization, with differences of up to 350 kPa around the perimeter. The recorded pressures exceeded the tunnel pressure by 100 to 400 kPa with the excess pressure attributable to the swelling of the clay. The horizontal pressure was expected to be equal at all points along the axis of the bulkhead but this was not the case, although the trend was towards equal pressure during heating. The bulkhead core did not show signs of increasing pressure until 1000 days of operation, which is consistent with a slower rate of water uptake. During heating, the hydraulic pressure in the clay increased causing the total pressures to also increase. With cooling, total pressures experienced a slight reduction.

Displacement transducers were used to measure the movement of the steel restraint and compression of the clay blocks was measured using a sonic probe extensometer. At the end of pressurization, the bulkhead had moved 10 mm downstream and was compressed by 64 mm at 4 MPa. Thus during pressurization, the clay mass was simultaneously being compressed and shifted as swelling pressures from the clay developed. Upon depressurization, 4 mm of clay bulkhead and 2 mm of steel shell rebound occurred.

Temperature was monitored throughout the bulkhead. During pressurization the temperature was largely unchanged at 17°C. During heating, temperatures increased the most adjacent to the chamber, reaching approximately 60°C in the upper portions of the bulkhead. There was a region of slightly higher temperatures (~5 to 8°C) adjacent to the pneumatically emplaced backfill as compared to the compacted *in situ* backfill. This material was at a lower dry density (1.85 vs. 2.15 Mg/m^3) and higher initial moisture content than the *in situ* compacted materials placed in the lower two thirds of the backfill wall. This created a more permeable region where heat would be more easily transferred to the bulkhead.

Sampling on decommissioning showed that the downstream face was not substantially different in terms of density and water content from the as-placed materials, i.e., water content ~ 15.5%, dry density ~1.92 Mg/m^3. When initially exposed during decommissioning, the original block interfaces were not open, however, after limited evaporation these interfaces became visible. The clay was wetter and less dense towards the top upstream side of the bulkhead, which showed evidence of considerable disturbance with an average water content of 33 % and an average dry density of ~1.45 Mg/m^3.

Thus the general response of the clay bulkhead was of physical adjustment to a number of influences, water flow, hydraulic pressure, compression of the blocks and swelling of the bentonite. The pattern of water uptake was not homogeneous and was influenced by differing material densities and locations relative to the water source. After approximately 1550 days of operation, the bulkhead was considered fully saturated and the pore pressures in the centre of the bulkhead were trending towards 4 MPa. The primary flowpath across the bulkhead was along the lower density shotclay material at the rock-clay interface, particularly near the tunnel crown.

VI. CONCRETE BULKHEAD RESPONSE

Many of the physical changes in the concrete bulkhead occurred soon after the beginning of curing. Volume reduction occurred during curing, causing a partial separation of concrete from the rock. During the first two weeks after pouring[5] the concrete also developed several macroscopic shrinkage cracks inside of the bulkhead (Figure 4). An acoustic emission system recorded acoustic events associated with the development of the cracks and loss of acoustic wave velocity and amplitude across the cracks. The nucleation points for these cracks were at the intersection of the keyed and unkeyed segments of the bulkhead. This suggested that tensile forces due to a combination of shrinkage and selective debonding of the rock-concrete interface were responsible. After grouting, velocity and amplitude increased across both the internal cracks and the rock-concrete interface, suggesting that they had been successfully filled. Subsequent acoustic emission monitoring suggests the cracks have not been reactivated since they were grouted. During curing the peak hydration temperature near the core of the bulkhead was 45°C, about 20°C above the as-placed temperature. The majority of acoustic events occurred during this time with 84% or 4088 acoustic events (AE) recorded in the concrete during the first month of curing. These were largely associated with the macroscopic shrinkage crack development. During the one-month period after grouting, only 14 events were recorded in the concrete. A total of 42 events were recorded during pressurization from 2 to 4 MPa. Totals of 489 events were recorded during the one year of constant 4 MPa pressure and ambient temperature, 215 events during heating and 39 events during cooling and depressurization. With the exception of the curing period most cracks were associated with the rock-concrete interface.

As suggested by the low number of AE events, the response of the bulkhead was relatively neutral during pressurization (Figure 4). Transducers on the bulkhead face indicated a maximum displacement of 0.2 mm in the downstream direction. The displacement was not symmetric, suggesting that portions of the bulkhead may have been restricted from movement by the interface contact. Piezometers near the test chamber showed pressures responding rapidly to tunnel pressure changes indicating a good hydraulic connection of the interface with the water in the chamber. Piezometers downstream of the point at which grout was injected on the interface showed negligible pressure change, suggesting that the grouting formed a low permeability gasket-type barrier at that point. Displacement transducers were also arranged to monitor the opening and closing of the rock-concrete interface in selected locations. The interface measurements indicated that the keyed inclined interface was closing and the vertical keyed interface opened slightly. Strain gauges indicated slight compression along the axis of the bulkhead during pressurization.

The concrete expanded during the heating phase, although this expansion was uneven since the heating was applied from only one side. The rock acted as a large heat sink so warm water moving along the interface did not warm the edge of the bulkhead (less than 2 L of water travelled along the interface daily). The heating front moved into the bulkhead more rapidly in the centre than near the perimeter. The strain gauges in the bulkhead showed a small expansion with heating. The bulkhead contracted during cooling but the bulkhead had not cooled to ambient temperatures at the conclusion of monitoring. The interface aperture did not change during the cooling, likely because the concrete was still warm and had not completely contracted.

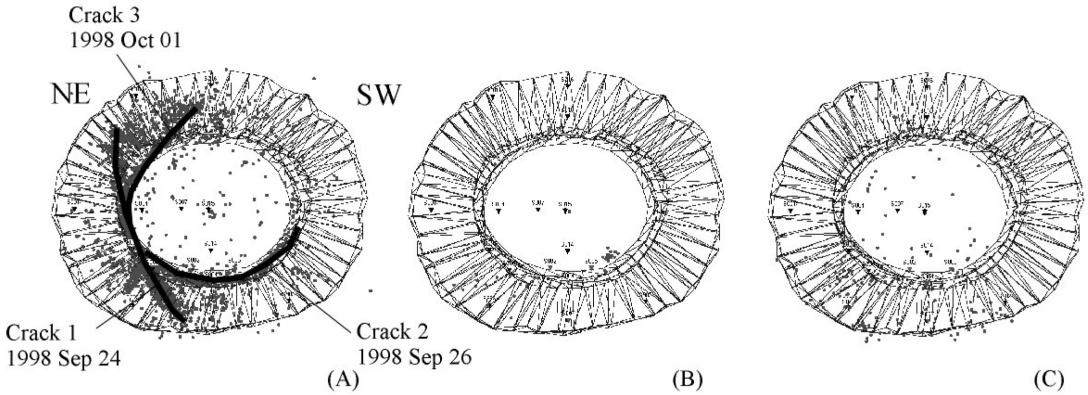

Figure 4: Acoustic emission events in the concrete bulkhead a) during curing b) during pressurization c) during heating.

VII. ROCK MASS RESPONSE

While the bulkheads were the primary focus of the TSX, the rock mass surrounding the bulkheads was part of the sealing system and was also monitored. Vertical and horizontal planes of hydrogeologic boreholes were monitored for pressure. Hydraulic pressures within the rock mass surrounding the tunnel were generally higher in the vertical boreholes than in the horizontal boreholes as a result of increased stresses in the roof of the tunnel and decreased stresses in the tunnel wall. This was a consequence of a high horizontal to vertical *in situ* stress ratio (6:1) and stress redistribution around the excavated tunnel. Hydraulic pressures initially reached as high as 5.5 MPa vertically, compared to 4 MPa horizontally. The hydraulic pressures within the first metre of rock mass showed a decrease in hydraulic pressure after excavation and before pressurization. During the pressurization of the tunnel the hydraulic response in the rock mass was limited to about the first metre of rock from the TSX tunnel perimeter. The hydraulic pressures within the rock mass beyond one metre from the tunnel wall showed little or no response to the different tunnel pressures.

Hydraulic pressure in the rock increased during heating and these hydraulic responses were largest within the first metre of rock reaching pressures exceeding 11 MPa above the tunnel and nearly to 9 MPa in the in the rock at the sides of the tunnel as a result of thermal expansion of trapped porewater. Increases in hydraulic pressure were also noted throughout the rock mass, however the magnitude of this increase diminished with distance from the tunnel. When the heaters were shut off in 2003 November, cooling resulted in rapid hydraulic pressure decreases being observed within the first metre of rock mass surrounding the tunnels and seals. The hydraulic responses observed beyond the first metre of rock mass were small and several borehole intervals demonstrated continuing increasing trends as a remnant of the outward moving thermal pulse.

VIII. LESSONS LEARNED

The TSX allowed the testing of candidate repository materials at full scale. The TSX showed it is possible to construct functional clay and concrete bulkheads to seal tunnels and limit axial flow. Prior to the experiment it was believed that the EDZ would be the primary pathway for water flow around the bulkheads but the keyed seals cut-off or reduced flow through the EDZ and the primary pathways were actually the rock-concrete interface and shotclay-rock interface.

The swelling clay bulkhead also demonstrated the ability to self heal and to adjust to differential displacements in its own mass without developing leaks but only if the water pressure was increased gradually. To accomplish this, the clay needed to be constrained to prevent volume expansion. In this experiment, a structural steel restraint system was installed although such a system would not be used in an actual repository design. The concrete bulkhead was able to withstand the loading from hydraulic pressure with minimal offset. This suggests concrete would make a suitable restraint for a swelling clay component of a seal.

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