The Tunnel Sealing Experiment: The Construction and Performance of Full Scale Clay and Concrete Bulkheads at Elevated Pressure and Temperature

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ABSTRACT

Concepts for deep geologic disposal of radioactive waste, as proposed by many international organizations, include bulkheads or plugs in the shaft, or at the entrances to disposal rooms, or both. The seals are primarily to prevent groundwater transport of radioisotopes along underground openings but also provide a measure of security by restricting tunnel access. 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 buffer barrier, the room, tunnel and shaft backfill and sealing materials). 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), a full-scale tunnel seal component study. The TSX showed it is possible to construct tunnel seals that limit axial flow under high hydraulic gradient and elevated temperature. The clay and concrete bulkheads had seepage rates of 1 mL/min and 10 mL/min at ambient temperature. Elevated temperatures caused a further decrease in seepage past the concrete bulkhead to approximately 2-3 mL/min.

1. INTRODUCTION

The TSX had two bulkheads (Fig. 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 bentonite-sand material (clay) blocks. 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 65°C at the face of each bulkhead. 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 [1] was conducted jointly at the URL by Japan Atomic Energy Agency (JAEA), 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 demonstrate technologies for construction of bentonite and concrete bulkheads, to quantify the performance of each bulkhead and to document the factors that affect performance. The second phase was conducted by JAEA, ANDRA and AECL [2].

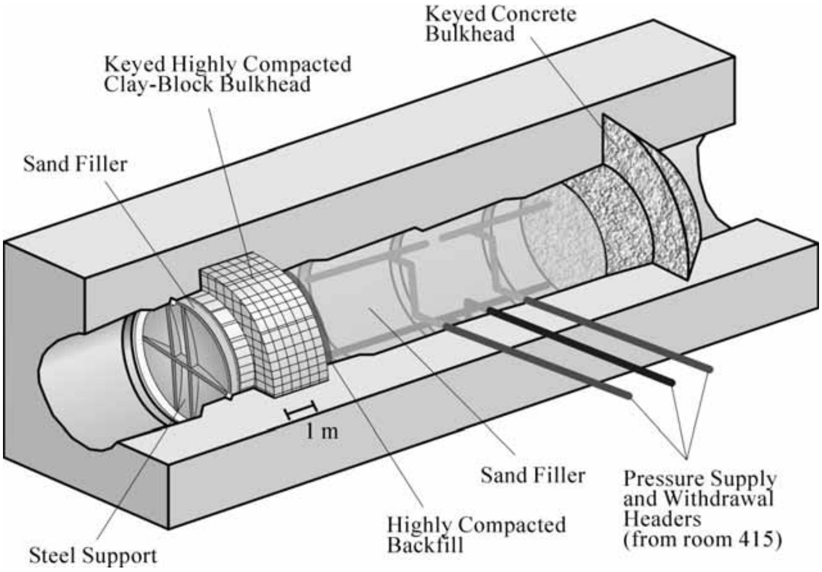

Fig. 1. Configuration of the TSX. Clay Bulkhead is 2.6 m thick; Concrete Bulkhead is 3.5 m thick

2. CONSTRUCTION AND OPERATION

The tunnel was excavated parallel to the trend of the maximum principal stress (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°), had a 3.5-m-high by 4.4-m-wide elliptical cross section and was 40 m in length using careful full faced drill and blast techniques. This was followed by excavation of the keys using a rock excavation technique developed at the URL called perimeter line drilling and rock splitting. Drilling delineated the perimeter of the rock area to be removed and the central mass was drilled and then hydraulic splitters were used to remove the rock. The rock mass was unfractured granite and granodiorite.

The 67 m^3 clay bulkhead was installed first along with its restraint system. In a repository, swelling clay would be restrained by concrete or backfill material. The restraint system, which was designed to withstand 4 MPa of hydraulic pressure and 1 MPa of swelling pressure, also permitted seepage collection via a geomembrane configured into different measurement zones. The system consisted of a rock bolted concrete bearing ring supporting an elongated hemispherical steel dome that had the loading evenly distributed via 1 m of silica sand confined by a stainless steel plate adjacent to the clay. The 2.6 m long clay bulkhead was comprised of 70% Kunigel V1 bentonite clay and 30% graded silica sand blocks with nominal dimensions of 0.1 m x 0.36 m x 0.20 m. The blocks were fitted together and crushed block material was used for gap fill. Before placement of the blocks, the walls of the clay key were pneumatically covered with 5 to 60 mm of shotclay material. The shotclay 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. As the clay bulkhead was being constructed, a 0.3 m thick 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 central portion of the tunnel was filled with sand after the clay bulkhead was built, as internal restraint and to reduce the volume of water used.

On the upstream side of the 76 m^3 concrete bulkhead, a 250-mm-thick wall was first 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 were composed of LHHPC. In LHHPC a substantial part of the Portland cement is substituted with pozzolanic silica fume and non-pozzolanic silica flour. A naphthalene-based superplasticizer was used to enhance workability of the concrete. These substitutions lower the heat of hydration and also reduce the pH of the cured concrete to the range of 10.6 [1]. The cement, silica fume and silica flour (in a 1:1:2 ratio) 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. Once the concrete bulkhead was cured, initial pressurization of the tunnel to 300 kPa showed high flow rates. Pressure was reduced and the concrete-rock interface was grouted through pre-installed grout tubes. Subsequent pressurization showed substantially reduced flow along the interface.

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 to a maximum of 4 MPa. Pressurization was planned for four months, but took place over a period of 19 months due to initial flow events past the clay bulkhead that showed time was required for hydration and associated swelling of the clay bulkhead to take place. In 2002 a heater loop was added to allow the temperature in the tunnel to be increased and the water circulated through the tunnel was heated until 2003 November reaching a peak temperature of approximately 65°C at the centre of the upstream ends of the bulkheads. The experiment was decommissioned in 2004 with samples taken from both bulkheads to confirm readings and determine physical conditions.

The TSX was monitored with over 900 instruments. Instrumentation recorded hydraulic pressure in and around the clay, concrete and rock; loading pressure in and around the clay; moisture content in the clay and concrete; damage development in the rock and concrete; strain in the concrete; displacement of the concrete and clay bulkheads; water flow into the tunnel; and temperature of the tunnel, concrete and clay. Seepage was recorded manually.

3. OBSERVATIONS

Initially there were high flows past the clay bulkhead, however, hydration and subsequent swelling of the clay reduced the seepage rate. Flow was primarily at the shotclay and clay-rock interface for the clay and at the interface for the concrete bulkhead. High seepage also occurred at the concrete-rock interface, requiring remedial cement grouting. Ultimately, at 4 MPa hydraulic pressure across these bulkheads, the grouted concrete bulkhead and the saturated clay block bulkhead had effective hydraulic conductivities of 10^{-10} m/s (~10 mL/min seepage) and 10^{-11} m/s (~1 mL/min seepage) respectively (Fig. 2). At elevated temperatures the rate was unchanged for clay but decreased to 2-3 mL/min for the concrete bulkhead. Tracer tests indicated a 19-hour transit time past the concrete bulkhead and 816 hours past the clay bulkhead at ambient temperature and 4 MPa pressure.

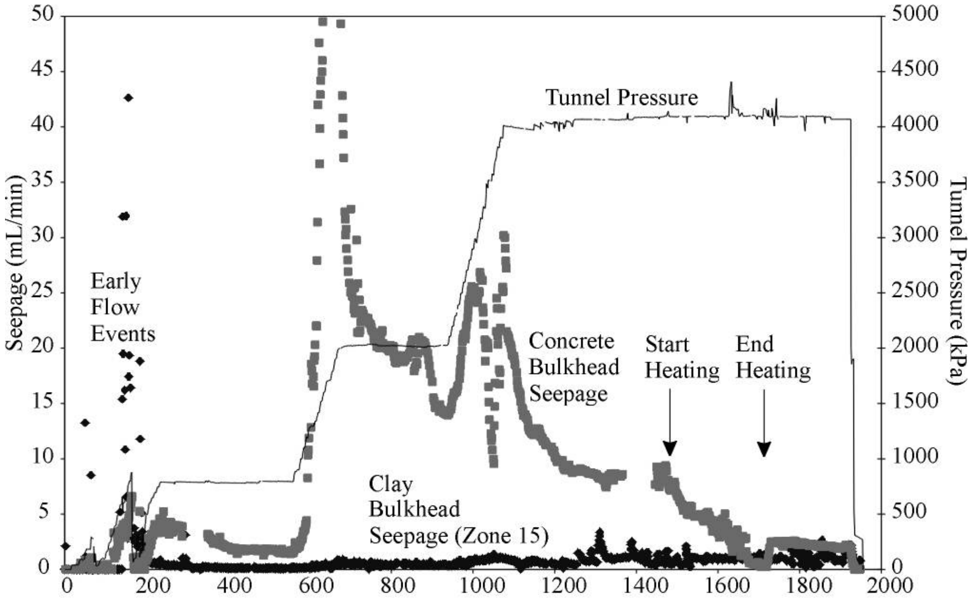

Fig. 2. Clay and concrete bulkhead seepage

The clay bulkhead saturated from the edges inward to the core, which was confirmed by suction and hydraulic pressure measurements and post-testing sampling. During heating more permeable regions showed no temperature related pressure increase while those in the core showed an increase indicating that water movement was more restricted in the clay bulkhead core.

The clay bulkhead showed a total of 54 mm of downstream displacement as a result of clay bulkhead and restraint system compliance. The displacement was confirmed by sampling that showed the clay near the upstream end had a lower density, indicating that the clay bulkhead had expanded to maintain contact with the rock and the backfill wall. 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. At the end of the test, block density ranged from 1.85-2.0 Mg/m^3 and water content ranged from 13-17%. The lower density (higher water content) material was near the upstream face and the higher density (lower water content) was located near the downstream face.

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%. At the end of the test, on the upstream side of the keyed section of the bulkhead, the shotclay had dry densities ranging from 1.0-1.5 Mg/m^3 and water contents of 30-60%, indicative of swelling to maintain contact with the rock surface. On the downstream end of the keyed section, the density was approximately 1.8 Mg/m^3 and the water content was approximately 18%.

The backfill wall was also fully saturated at the end of the test. The lower compacted backfill was placed at 2.1 Mg/m^3 and 5% water content and was approximately 2.2 Mg/m^3 and 8.5% at the end of the test. The upper, pneumatically placed portion was placed at 1.5-1.9 Mg/m^3 and 14-28% water content and was approximately 2.2 Mg/m^3 and 8.5% at the end of the test. Some expansion of the backfill material occurred into the gap at the crown of the sand-filled pressure chamber, causing decreased backfill density near the roof of the tunnel.

Three unusual features were noted during decommissioning of the clay bulkhead: the first was small, unconnected relict bands or pockets of eroded material in the crown region of the keyed portion of the bulkhead and extending perhaps 1/3 of the way down the wall of the clay key. The second was a series of very thin, unconnected, relict flow channels along the contact between clay blocks closest to the sidewall of the clay key. The third was a region that contained air bubbles in the uppermost portion of the upstream face of the clay key where the shotclay was least dense and escape of trapped air was impossible. Given the observed seepage rates in the clay bulkhead, none of these features is believed to have substantially affected clay bulkhead performance.

The concrete bulkhead showed only 0.2 mm of axial displacement from hydraulic pressure loading and 0.7 mm of axial thermal expansion. The concrete bulkhead was monitored by an array of acoustic emission (AE) sensors and showed that 84% of the AE activity occurred within a few weeks of pouring due to formation of three internal cracks. These formed due to internal stresses related to shrinkage associated with curing and the shape of the bulkhead. The cracks were filled during grouting of the interface. The remaining AE activity mainly occurred once the full 4 MPa tunnel pressure was reached (10%) and during heating (4%). The remaining events occurred during pressurization and end of test depressurization, suggesting the concrete bulkhead acted as one stable mass once it had cured, and had been grouted.

At the concrete bulkhead, piezometers indicated that the grout injection location acted as a gasket. Pressure in the interface upstream was similar to the tunnel pressure, while the pressure downstream from the injection location was essentially zero.

The concrete mass appeared homogeneous on the macroscopic scale in terms of material distribution, however, the measured properties of the concrete indicated some spatial differences in the concrete. Porosity measurements ranged from 11% on the downstream end to 6.5% on the upstream end. The upstream values are similar to those found in high performance concrete (such as LHHPC), while the downstream end porosity value is similar to that found in regular concretes. Sonic velocity ranged from 4300 to 4800 m/s, with lower velocity near the downstream end of the concrete bulkhead and higher velocities near the centre of the bulkhead, however, the sonic velocity measurement closest to the downstream face had a magnitude similar to that of the bulkhead core. Water supplied to the bulkhead face on the inside of the downstream formwork may have aided in decreasing void formation during curing for a shallow depth of concrete. The transmissivities from the centre of the bulkhead were on the order of 10^{-15} m/s based on *in situ* testing. Near the upstream and downstream ends the transmissivities were approximately one to two orders of magnitude higher. The concrete-rock interface and cracks returned magnitudes on the order of 10^{-12} m/s. Scanning electron microscope images showed the edges of the concrete to have more microcracks and some ettringite formation. The compressive strength of the bulkhead averaged 77 MPa, indicating that on average, the concrete did not gain much strength beyond its predicted 28-day strength of 70 MPa. However, the upstream strength value was approximately 100 MPa, suggesting a lack of water in the bulkhead core and downstream locations may have inhibited strength increase. The measurements indicate a less permeable core with some perimeter microcracking that likely resulted from drier conditions at the perimeter.

4. SUMMARY

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 concrete-rock interface and clay-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 or flow past it can be controlled. In the TSX a structural steel restraint system was installed providing mechanical support but not seepage resistance. The concrete bulkhead was able to withstand the loading from hydraulic pressure with minimal offset and once grouted provided considerable hydraulic resistance. This suggests concrete would make a suitable restraint for a swelling clay component of a seal.

5. REFERENCES

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