Full-Scale Tunnel and Shaft Seals: Tunnel Sealing Experiment (TSX) and Enhanced Sealing Project (ESP) at Canadian Underground Research Laboratory (URL)

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Full-scale shaft and tunnel sealing installations were constructed at Canadian Nuclear Laboratories (CNL), Underground Research Laboratory (URL) as part of multinational co-operative research projects. The Tunnel Sealing Experiment (TSX) consisted of full-scale concrete plug and a bentonite-based bulkhead installations, both keyed into the tunnel. The region between these two components was sand-filled, flooded and hydraulically pressurized to 4.2 MPa and then heated to 85°C. The effects of hydraulic pressure and temperature on seal performance and the surrounding rock were monitored, allowing evaluation of the system's Thermal-Hydraulic-Mechanical-Chemical (T-H-M-C) evolution. Both components provided effective hydraulic barriers. In 2009 the Enhanced Sealing Project (ESP), a plug consisting of concrete and in situ compacted bentonite was installed at a depth of ~ 275m in a drill and blast excavated shaft. The Thermal-Hydraulic-Mechanical (T-H-M) conditions have been to determine the interactions between the Fracture Zone (FZ), the seal and the Excavation Damaged Zone (EDZ) adjacent to it. It has also provided valuable information regarding the nature of hydraulic interactions vertically across a low-permeability seal. A second seal constructed using precompacted bentonite blocks was installed in a bored shaft to complete the isolation of the lower sections of the URL.

The TSX and the ESP have provided valuable information regarding construction of full-scale tunnel and shaft seals that effectively restricted water movement past them in a repository-type environment. They have also provided valuable field data, against which numerical simulations can be tested, improving confidence in numerical predictions related to post-closure system evolution.

1. Background

Canadian Nuclear Laboratories (formerly Atomic Energy of Canada), operated an Underground Research Laboratory (URL) in a granitic pluton within the Canadian Shield since 1980. In 2007 decommissioning of the facility was initiated and the surface facility removed in 2014. During the URL's operation, the URL was host to numerous repository sealing investigations in various-scale experiments. Two of the large-scale experiments were the Tunnel Sealing Experiment (TSX) in 1997-2007 and the post-closure Enhanced Sealing Experiment (ESP) 2009-2016 (ongoing).

The TSX was an internationally-funded project involving WIPP (USA), Andra (France) and JNC (Japan). It consisted of two independently constructed and monitored components: a 3.5 m-long un-reinforced concrete plug and a ~2.6 m long bentonite-based bulkhead, both keyed into the tunnel (Fig. 1). Located in a tunnel excavated in the highly stressed rock at the 420 Level of the URL the region between these structures was sand-filled, flooded, pressurized to 4.2 MPa and heated to 85°C and the effects of hydraulic pressure and temperature being monitored.

The ESP is an international collaboration Research Development and Demonstration Project that has been funded by Andra (France), CNL (Canada), NWMO (Canada), Posiva (Finland) and SKB

(Sweden) at various times during the period 2009-2016. Two shaft plugs, spanning a water-bearing fracture (FZ-2), were installed at a depth of approximately 275m below ground surface as part of closure of the URL. The first plug was installed in a drill and blast excavated access shaft and the second in a raise-bore ventilation raise. These composite plugs consist of a 3m-long densely compacted bentonite-sand component sandwiched between two 3m-long concrete segments (Fig. 2) in the 4.8m diameter shaft. In the beginning of the experiment, the URL was artificially flooded to within 1 m of the shaft seal's base. As the region above the plugs has naturally flooded, the thermal-hydraulic-mechanical evolution of the plug located in the access shaft has been monitored. Since the access shaft and ventilation raise are connected at 240 and 420 level, if either plug failed, the response would be seen in the sensors monitoring the main shaft plug.

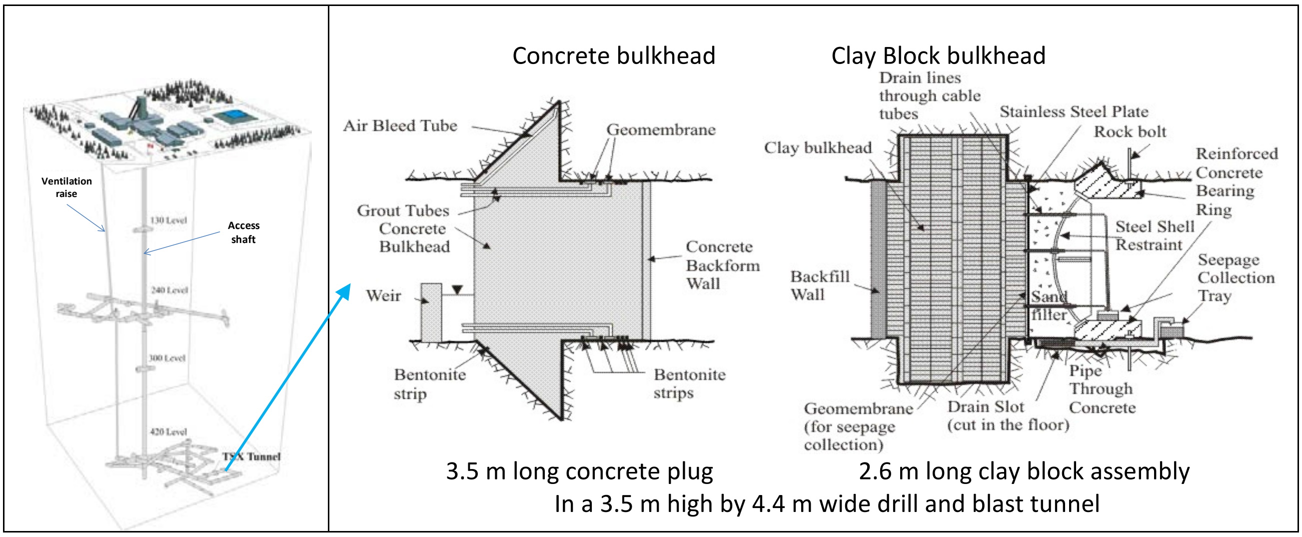


Fig. 1. Tunnel Sealing Experiment (TSX) at -420 m Level of URL (Martino et al. 2008)

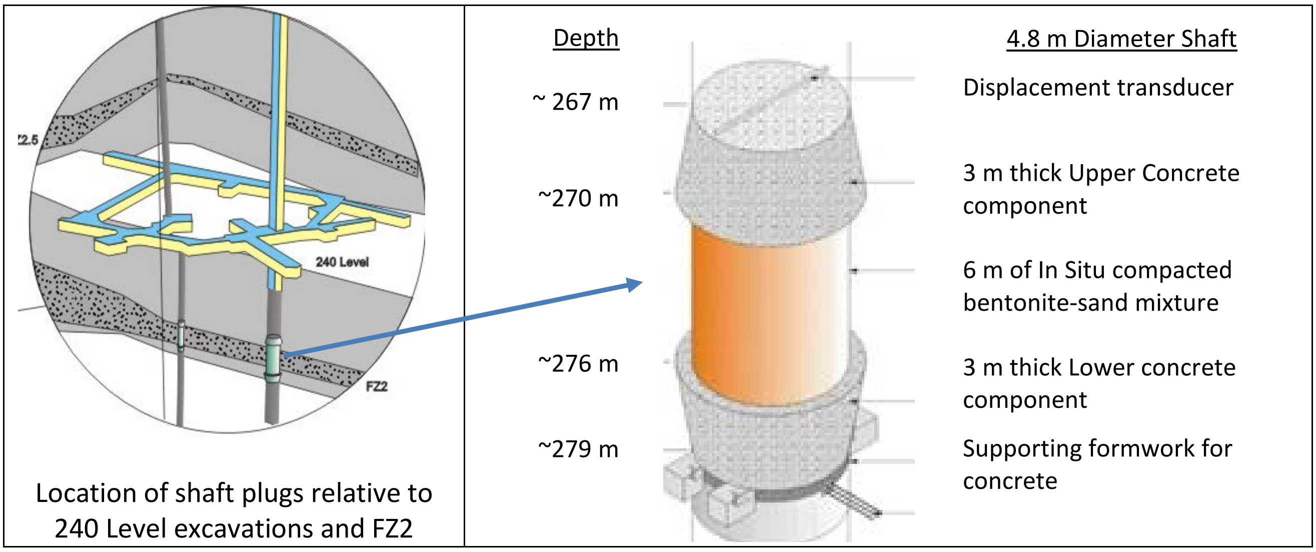


Fig. 2. Enhanced Sealing Experiment (ESP) (Dixon et al. 2012)

2. Scope, Objectives and Methods

Both the TSX and ESP were designed with the intent of demonstrating the constructability of full-scale sealing systems for isolation of tunnels and shafts of the types that would be encountered in a repository for nuclear fuel waste. Beyond basic demonstration of construction, these installations were intended to provide information on the evolution (thermal, hydraulic, mechanical, and chemical) of plugs installed in a deep geologic environment. This was accomplished through construction of these structures using conventional technologies (block and in situ compacted bentonite-based sealing materials and low-heat, high-performance concretes). Associated with each installation, was an extensive monitoring system that tracked the evolution of the clay, concrete and adjacent rock mass. In both projects the plugs for the TSX and ESP were monitored for periods of 10 and 7+ (ongoing) years, respectively. Ultimately the information gained provides field data for use in developing numerical models to predict their T-H-M and Chemical evolution.

3. Methods

The TSX and ESP required use of sensors that were physically modified to ensure their survival under the harsh T-H-M conditions present. These installations also allowed various sensors and sensor technologies to be evaluated for their potential use in repository-type environments.

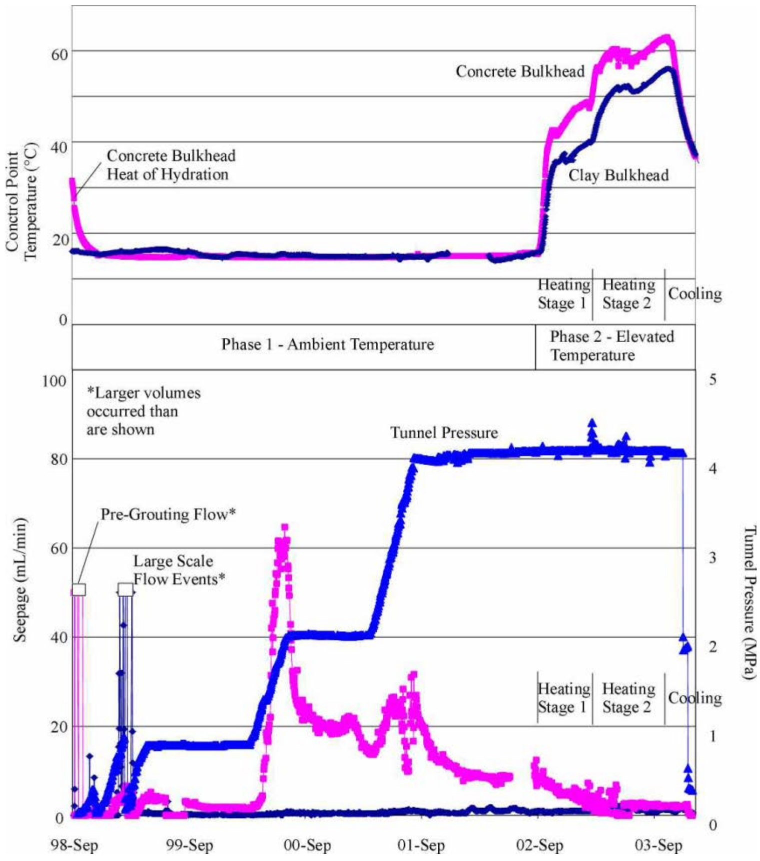
The TSX required monitoring of: temperature of the seals, the development and transfer of hydraulic and mechanical pressures within the seals, at their interface with the surrounding rock mass and within the adjacent rock. Additionally, water uptake by the initially unsaturated bentonite sealing materials needed to be tracked. Sensors used in the collection of these data included: psychrometers and TDR's for water uptake monitoring, vibrating-wire total and hydraulic pressure sensors, fiber-optic strain sensors (for concrete shrinkage) and thermocouples for temperature monitoring. Additionally an extensive seepage monitoring and collection system was installed at the downstream face of each bulkhead. The geosphere in the vicinity was also monitored for generation of microfractures and an excavation disturbed zone through use of micro-seismic and acoustic emission monitoring systems. In total 928 sensors (including 365 temperature sensors), were installed in the TSX (Martino et al. 2008).

The ESP is a less intensively instrumented installation requiring monitoring via sensors capable of providing output to distantly located dataloggers (~275m up a flooding vertical shaft Dixon et al. 2012). This constrained the usable technologies. The ESP was instrumented to monitor the same types of parameters as the TSX: temperature, hydraulic and mechanical pressures as well as water uptake by the clay. Moisture sensing technologies included psychrometers and TDRs. Total and hydraulic pressures were monitored using both fibre-optic and vibrating wire sensors. Fibre-optic sensors were used to monitor concrete strain during curing and a variety of thermal couple and thermistors were used to monitor temperature changes. In total, 100 sensors were installed in the ESP, of which 36 were intended to track longer term (>4 years) H-M evolution. The closure and demolition in 2014 of the surface facilities at the URL meant that the system needed to transition from a fully automated indoor location to an unserviced, stand-alone facility.

4. Results and Discussion

4.1 TSX

Monitoring of the TSX was primarily focussed on evaluating the effectiveness of the two bulkhead components in restricting water flow. The influences of hydraulic head and temperature on the flow were determined as well as the saturation process associated with the clay bulkhead (Fig. 3). The chamber between the two bulkheads was successfully pressurized to 4.2 MPa and heated to 85°C, although the concrete and clay bulkheads only achieved approximately 62°C and 55°C, respectively, during the time the TSX was operated. The concrete bulkhead, although composed of low-heat, low-pH, low-shrinkage, high-performance concrete exhibited sufficient localized shrinkage to generate preferential water flow paths at several locations along the concrete-rock interface. This required post-grouting to be undertaken, an activity that was planned for in experiment design through the installation of several grouting rings at the time of bulkhead construction. Grouting successfully reduced the seepage past the concrete from >0.05 L/min to <0.002 L/min at ~800 kPa hydraulic pressure in the central chamber. The concrete bulkhead showed several notable changes in flow past it over the course of time after grouting with seepage reaching ~0.065 L/min approximately 2 years after grouting. With time (2 more years), seepage decreased to ~0.01 L/min, even as the hydraulic pressure was increased to 4.2 MPa, likely as the results of bentonite fines from the pressure chamber fill entering and clogging the flow paths. When the system began to be heated, seepage decreased further, reaching approximately 0.003 L/min under a 4.2 MPa hydraulic head at the time of test termination.



Main Observations:

Concrete Bulkhead

-Post-grouting of concrete reduced seepage from >0.05 to <0.004 L/min @800 kPa.
-Seepage past concrete decreased with time.
-Heating resulted in further reduction in seepage.
-End-of-Test seepage rate was ~0.003 L/min at 4.2 MPa hydraulic head

Clay Bulkhead

-Early stage hydration exhibited several large flow events but no discernible erosion of clay.
-Flow was largely limited to block interfaces (during initial hydration period) and the rock-clay interface once near-saturation was achieved.
-Once initial clay hydration was achieved seepage was extremely low, <0.002 L/min.

Rock

-Rock around TSX was stable while installation was pressurized and bulkheads present.
-Post-test saw re-activation of stress-induced rock damaging processes.

Fig. 3. Evolution of temperature and seepage past TSX bulkheads (Martino et al. 2008)

4.2 ESP

Monitoring of the ESP is an ongoing activity as of 2016. The main shaft seal is very gradually taking on water and approaching saturation. The moisture sensors installed in the clay near the rock-clay and concrete-clay interfaces showed rapid saturation while the core of the main shaft seal has shown more gradual wetting (Fig. 4), as water moves slowly through the saturated perimeter clay.

The ESP is being done at ambient temperature (~11°C) and saw only a brief thermal disturbance as concrete curing occurred. In the initial phase of the ESP, rapid pressurization of the region below the seal and gradual pressure increase in the region above it. It was anticipated and observed, that even though the concrete used was low shrinkage, there would be open interfaces between the rock and concrete. The concrete components were designed such that their only role was to constrain the clay and prevent it from swelling out of its as-placed location. Steadily increasing hydraulic pressure above the seal is being observed as the shafts continue to flood (Fig. 5), (Priyanto et al. 2015, 2016). Were there to be an open or easy connection for water movement past the shaft seal then the hydraulic pressures along the length of the shaft would be entirely attributable to the elevation head. This is not what has been observed with a substantial pressure differential developing across the clay component. There was some evidence of partial over-pressure release during 2011-2012 but the pressure across the seal never decreased levels attributable to hydraulic head alone.

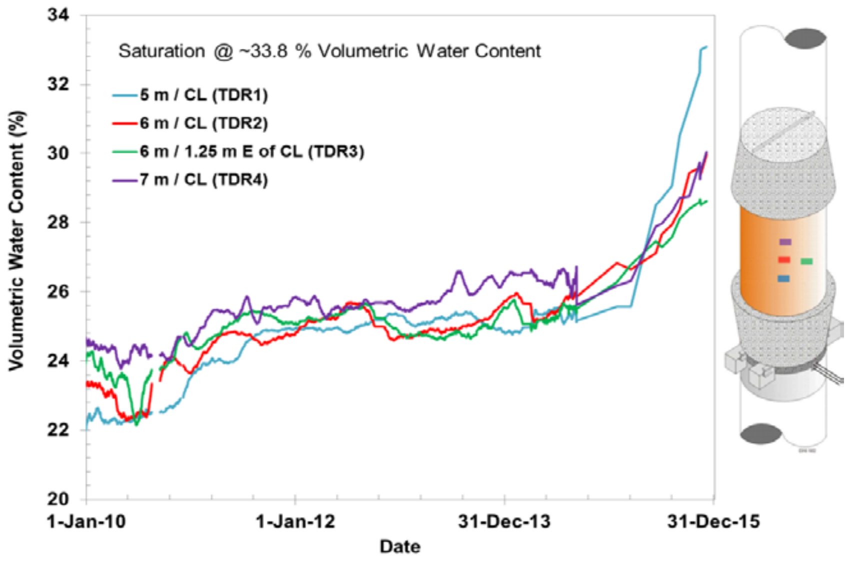


Fig. 4. Water uptake in core of clay plug (TDR data) (Priyanto et al. 2016)

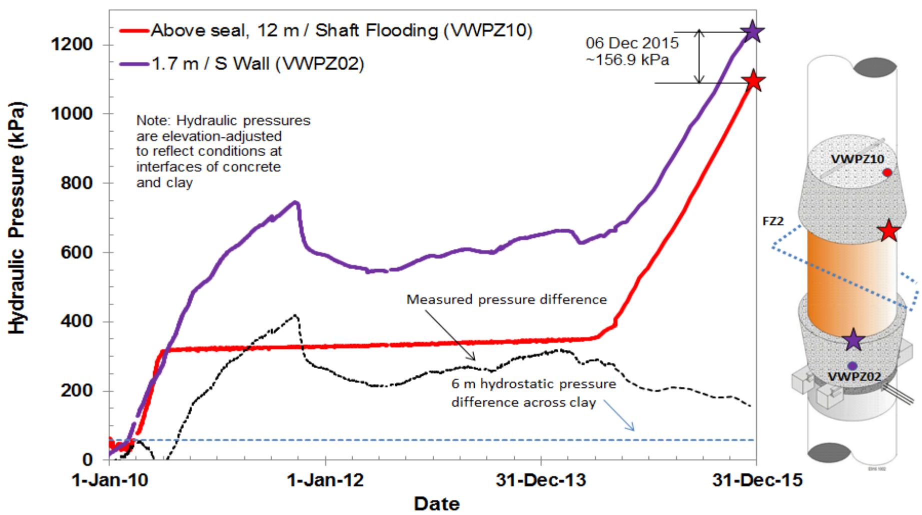


Fig. 5. Hydraulic pressures above and below main shaft plug (Priyanto et al. 2016)

As of mid-2014, the large horizontal developments at the 240 Level of the URL were completely flooded and water began to rise rapidly into the open shafts. This has resulted in substantial ongoing hydraulic pressure increase above and below the plug. Although the hydraulic pressure increases above and below the plug have shown similar rates of increase, a differential between the two regions has been maintained, although it is very gradually decreasing. This is interpreted as indicating that the lower region is only very poorly connected with FZ2 and FZ2 is similarly poorly connected to the open shaft. As there is no direct connection between the upper and lower shaft sections, a pressure difference is observed since excess hydraulic pressure is not able to be relieved quickly enough to eliminate the gradient. This condition may continue to exist for a considerable time if the connection between the open and isolated shaft sections remains poor. If the current flooding rate of ~3000 L/day continues, the upper shafts should flooded after August 2018.

4.3 Numerical Modelling of TSX and ESP

The TSX and ESP have been used in the development of numerical models developed to describe and predict performance and evolution of tunnel and shaft seals, as well as the geosphere immediately surrounding them. Examples of numerical modelling completed using these data are: Guo et al. (2003, 2005, 2006) TSX and Priyanto 2011, Priyanto et al. (2014a, 2014b, 2015) ESP.

5. Conclusions

The TSX and ESP have demonstrated, at full-scale, the ability to construct plugs and seals that can be installed in a deep geological environment where severe spatial constraints and environmental conditions are present. These installations have allowed for monitoring of the evolution of seals and plugs under natural and accelerated water uptake, providing valuable field demonstration data for use in developing and calibrating numerical models that can be used to describe and predict seal evolution. They have also highlighted the importance of field tests as unanticipated processes can complicate prediction of system evolution.

Acknowledgements

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