ENHANCED SEALING PROJECT: MONITORING THE THM RESPONSE OF A FULL-SCALE SHAFT SEAL

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ABSTRACT

Closure of the subsurface facilities at Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory (URL) was completed in 2010 with installation of a concrete surface cap. Additionally, as part of decommissioning, seals were installed at the penetration of the shafts through the major hydro-geological feature known as Fracture Zone 2 (FZ2). The seal construction was funded by Natural Resources Canada (NRCan) under the Nuclear Legacy Liabilities Program (NLLP).

The shaft seals at the URL were based on the composite seal concept developed for application in a deep geological repository for disposal of used nuclear fuel. The access shaft seal consists of two 3-m thick concrete segments that rigidly confine a 6-m long section of swelling clay-based material (40% bentonite clay – 60% sand by dry mass). Monitoring of the regional groundwater recovery following flooding of the lower shaft is a closure requirement and was included in the design. It was widely recognized that the installation of the seals at the URL represented a unique opportunity to monitor the evolution of the type of seal that might be installed in an actual repository but the NLLP mandate did not include any monitoring of shaft seal evolution. As a result the Enhanced Sealing Project (ESP) partnership composed of NWMO, Posiva, SKB and ANDRA was established and a set of 68 instruments (containing 100 sensors) were installed to monitor the evolution of the seal.

In the first year of operation sensors have monitored the following parameters in the ESP: thermal evolution and strain of the concrete components, thermal, hydraulic and mechanical changes in the clay component and its contacts with the rock and concrete confinement. Additionally, monitoring of the near-field and regional groundwater evolution has been undertaken. Monitoring of the short-term thermal-mechanical evolution of the concrete components was successfully accomplished and only a small temperature rise occurred due to the use of low-heat, low-pH, high-performance concrete. The temperature, moisture and pressure sensors installed in and around the clay component indicates that the groundwater pressure is quickly recovering in the vicinity of the shaft, the clay portion is providing a hydraulic disconnect between the regions above and below FZ2 and water uptake by the clay is progressing much as anticipated. The instrumentation and monitoring results up to the end of April 2011 are described in this paper.

1. BACKGROUND

This document summarizes the data collected as part of monitoring the concrete and bentonite-based shaft seal components at AECL's Underground Research Laboratory (URL). Physical closure of the URL was done as part of work funded by Natural Resources Canada (NRCan) under the Nuclear Legacy Liabilities Program (NLLP), but did not include monitoring of the structure following installation. Installation and monitoring of sensors intended to record the thermal, hydraulic and mechanical evolution of the main shaft seal is being done as part of a joint NWMO, SKB, Posiva, ANDRA project (Enhanced Sealing Project, ESP).

As described in the papers and reports documenting the design and construction of the ESP [1], [2], [3], two shaft seals were installed at the URL, one in the access shaft and a second in the smaller diameter ventilation shaft (Figure 1). These seals are located at the intersections of the access shaft and ventilation shaft with a major water-bearing fracture (FZ2, shown in Figure 1). This feature represents the boundary between the two groundwater regimes at this site. Only the access shaft seal had monitoring sensors installed in it and so discussion in this paper is limited to evolution of the access shaft seal.

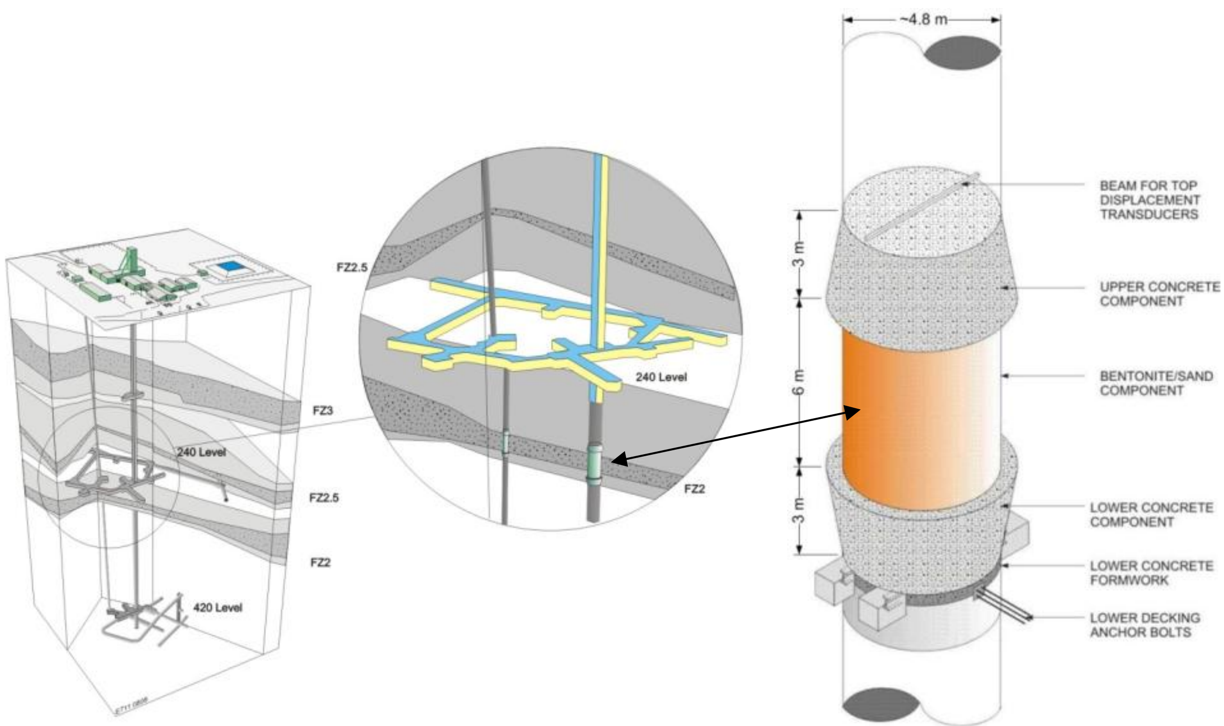


Figure 1. Geological structures, location of shaft seal and shaft seal geometry (note that geological features are not shown to scale).

The access shaft has a nominal diameter of 4.8 m and is sealed by a composite construction consisting of a 6-m-thick in situ compacted clay core. The clay component was composed of a blend of 40% Wyoming bentonite and 60% local quartz sand (generally referred to as clay-sand in the remainder of this report). This material is rigidly confined between two 3-m-thick concrete components (Figure 1). Both of the concrete components are keyed 0.5 m into the shaft wall, giving them a conical frustum shape. The lower concrete component is constructed of reinforced concrete that is designed to support the weight of all overlying materials. The upper concrete component is an unreinforced structure designed to restrain the clay-sand mix as it hydrates and swells. Detailed descriptions of the design and construction of the shaft seal are reported elsewhere and so are not repeated in this paper [1], [2], [3].

2. MONITORING OF THE ESP

The ESP formally consists of the instrumentation in and the monitoring of the access shaft seal. Its goal is to monitor the thermo-hydro-mechanical (T-H-M) behaviour of this full-scale repository-type shaft seal and record its evolution as the clay-sand mix saturates, the shaft floods and the regional groundwater pressures recover. This is accomplished by remotely monitoring a suite of 100 sensors (mounted in 68 instruments), installed in and around the shaft seal. The instruments measure a variety of T, H and M parameters, including concrete, clay-sand and rock temperature, total pressure within the clay-sand and at contacts between each of the components, hydraulic pressure in the rock, at the rock-concrete interfaces and within the clay-sand itself. Moisture conditions within the clay-sand mix are monitored using suction sensors (psychometers) as well as time-domain reflectometers (TDR). The evolution of the concrete component is monitored through temperature sensors and strain gauges. The location of the plug within the shaft is monitored by displacement sensors mounted at the upper surface of the concrete. The instrumentation installed in the shaft seal is described in detail in documents describing the ESP construction and initial monitoring results [2], [3], [4] [5]. Monitoring of the recovery of the regional groundwater pressures is accomplished via a series of surface boreholes located within ~750 m of the shaft.

2.1 Temperature monitoring

A large proportion of the instruments installed in the access shaft seal (e.g., vibrating wire piezometers, vibrating wire total pressure cells and psychrometers) contain temperature sensors as part of their construction. An additional 5 thermocouples were installed in each of the concrete components in order to capture the thermal evolution of this component. In total there are 8 temperature sensors within the lower concrete component and 13 in the upper concrete component. The temperature change being monitored is the result of the heat of hydration of the concrete and the subsequent cooling of the structure to the ambient temperature at the location of the shaft seal. This temperature gradient is an important aspect of the monitoring, as a high gradient could lead to thermally induced cracking during curing of the concrete. Beyond the thermal transient induced by the concrete heat of hydration, the shaft seal is expected to be thermally passive, remaining close to the ambient rock temperature (~11-12 ^{o}C).

Figure 2 (left side) shows the temperature evolution within the lower and upper concrete components at the warmest locations observed (centre of mass-poured volumes). The instruments in the lower concrete component recorded an as-placed concrete temperature of approximately 23.5°C and a peak temperature of 39.5°C. This is a concrete hydration temperature rise of approximately 16°C. For the upper concrete component, the nominal, as-placed temperature was 17°C, with a maximum temperature of 35.6°C, a hydration temperature rise of approximately 18.6°C. These values are close to the expected temperature rise for the low heat concrete mix [6] and are comparable to the 20°C increase observed for a similar mix used in AECL's Tunnel Sealing Experiment [7]. It should be noted that a similar mass of conventional, high cement content, high performance concrete would be expected to have experienced a temperature rise in the order of 60^{o}C to 70^{o}C [6] and is a material that experiences much more thermally-induced volume change.

The slightly larger rise in temperature observed in the upper component (a 2.6^{o}C difference), is attributed to two main factors. The first is that the upper component does not contain any heat conducting steel reinforcement (the lower concrete component is heavily reinforced, resulting in faster heat dissipation). The second factor is the insulating effects of the underlying clay-sand mix materials on the ability of the upper concrete mass to radiate heat during curing.

Figure 2 (right side) shows the temperature effect that concrete curing had on the adjacent clay-sand materials. The maximum temperature rise in the clay-sand component immediately adjacent to the concrete was only 14.3^{o}C and heat dissipation was essentially complete within ~60 days. This is not sufficient to alter the clay component mineralogically or have any discernible effect on its hydraulic or mechanical behaviour. To simplify labeling of the figures used in this report the following

2.2 Strain and displacement

The shaft seal is being monitored for internal strain of the concrete as it cures, as well as for movement of the upper surface of the entire seal.

The expansion and contraction of the concrete during the curing process continues to be monitored using fibre optic deformation sensors. Five sensors are mounted in each concrete component, allowing both radial and vertical strains to be monitored. Strains resulting from applied loading from hydraulic and swelling pressures will also be captured by these sensors. Figure 3 shows a comparison of the average shrinkage strains measured in both concrete components during approximately the first five months of curing. The measured shrinkage strains in the upper and lower concrete components averaged 340 and 225 microstrain units respectively, and leveled off after roughly 100 days. The substitution of pozzolans for a portion of the cement powder in the mix slows the rate of hydration so duration over which drying shrinkage related to curing is extended [6]. The upper concrete component exhibited approximately 50% more shrinkage than the lower concrete component due to dissimilarities in their construction (the lower concrete component is heavily reinforced and the upper concrete component is unreinforced). If these strains are considered to be uniformly distributed, and assuming complete debonding of the concrete-rock contact, the shrinkage would result in a gap roughly 0.6 mm wide forming around the perimeter of the lower concrete component and 0.9 mm wide around the upper concrete component. Evidence of partial debonding was found in previous work with large concrete seal components, resulting in highly water conductive concrete-rock interfaces [7]. These gaps would influence water access to the clay-sand mix and porewater pressure distribution, but due to concrete plug geometry should not affect the mechanical stability of the structure.

The vertical displacement of the top surface of the shaft seal (top surface of the upper concrete component) is being monitored using two fibre optic displacement transducers (Figure 3). These measure any vertical movement of the upper concrete component that may occur as the clay-sand material swells and applies increasing pressure to the base of the upper concrete component. These transducers are mounted to a rigid steel beam located approximately 30 cm above the top surface of the shaft seal, thereby providing a stable datum for displacement measurement. The positioning of the sensors allows any rotational movement of the concrete component to be detected. The downwards displacement of the base of the seal is not monitored. The massive steel beams installed below the lower concrete section should not allow for any discernible downwards displacement. A small shift in both sensors was observed in July 2010. Given the differing direction of the movements between the two sensors and the non-repetition of the occurrence, this shift may represent a single very small tilting of the concrete component

(<0.035 mm) that occurred in a single event. Such a small magnitude and isolated movement is not of sufficient magnitude to cause concern regarding seal performance or stability and likely indicates normal adjustment of the concrete mass.

2.3 Water uptake by clay-sand component

Water uptake in the clay-sand component is being monitored by two different types of sensors; time domain reflectometry probes (TDR) and thermocouple psychrometers. There are a total of fourteen psychrometers which measure localised conditions and four TDR probes that monitor moisture conditions in a more substantial volume installed in the clay-sand material.

The psychrometers provide a measure of relative humidity in the pore air and this can be related to suction and hence saturation of the clay-sand. A suction of roughly 6 MPa indicates a gravimetric moisture content of ~12% (saturation 65-70%), approximately the condition at the time of clay-sand installation. As the clay-sand takes on water, the suction decreases until it reaches approximately 0.5 - 1 MPa, (the osmotic suction of the clay-sand at full saturation). Values of < 500 kPa are generally associated with flooded sensors and so locations with such readings are generally assumed to have achieved 100% saturation. These sensors are particularly useful in areas where a saturation front is anticipated to rapidly pass through a volume of soil and so most were installed in the perimeter regions in the volume occupied by the clay-sand component. At the end of 2010, only two psychrometers have yet to register (near-) saturated conditions. These two psychrometers are installed in areas of the shaft seal that are physically more distant from major sources of water inflow and are showing, as expected, a slower rate of water uptake. Figure 4 shows examples of water uptake measured using these sensors, a more detailed discussion of these sensors are provided in other documents [2], [5].

The TDRs are indicating only a small and slow change in water content in the core of the clay-sand component (Figure 5), which is to be expected for a system that is slowly wetting from its perimeter. TDR probes are best suited to locations where wetting is slow and water content is fairly uniform over a larger volume, so they were located closer to the core of the region occupied by the clay-sand. These probes measure the bulk dielectric constant of the clay-water system and since the dielectric constant of water is high relative to other constituents, the bulk dielectric constant of the clay-sand mix can be related to its volumetric water content. The TDR datalogging system was installed in a water- and pressure- tight housing, so it should remain operational indefinitely [2].

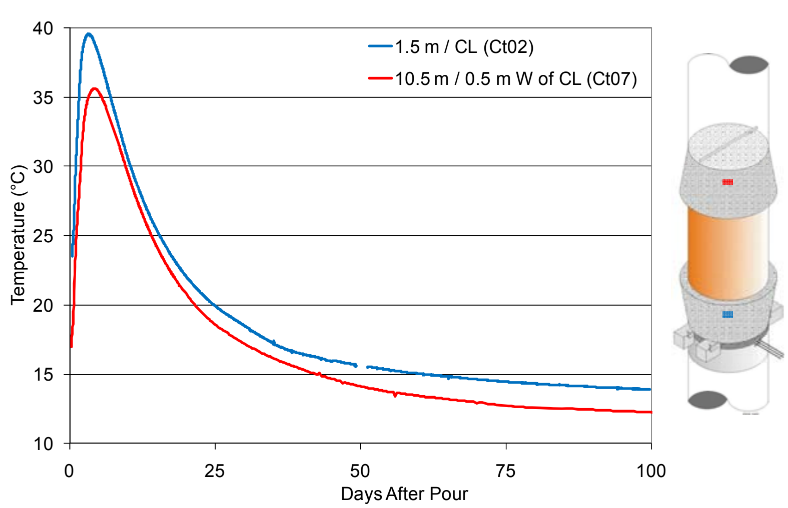
The TDR's were installed in blocks having slightly different initial water contents providing a means of calibrating them [2], [4]. In Figure 5 TDR-1, 2, 3 are showing evidence of gradual water uptake as of September 2010 while TDR 4 showed little change until February 2011. This can be attributed to the high degree of initial saturation of the material surrounding TDR 4. That sensor was installed in a precompacted block of clay-sand that was intentionally wetter so as to provide a calibration value for the other sensors [4], [5].

2.4 Water pressures and flooding of the URL

Hydraulic pressures, including water head above and below the plug, porewater pressure in the clay-sand component, pressures in the adjacent near-field rock mass are being monitored using 13 vibrating wire and 5 fibre optic piezometers. The groundwater level in the far-field rock, up to 500 m from the URL's access shaft, is monitored by fifty piezometers installed in twenty-two boreholes on the URL site.

These sensors are being used to determine the following:

- elevation of water within the URL shaft above the seal location,
- the hydraulic connection between water in the shaft and the clay-sand component via the concrete-rock interfaces,
- recovery of porewater pressures in the near-field rock adjacent to the shaft seal,
- saturation of the clay-sand component (porewater pressure indicates saturation), and
- recovery of the groundwater pressures in the rock surrounding the URL due to passive flooding of the underground excavations.



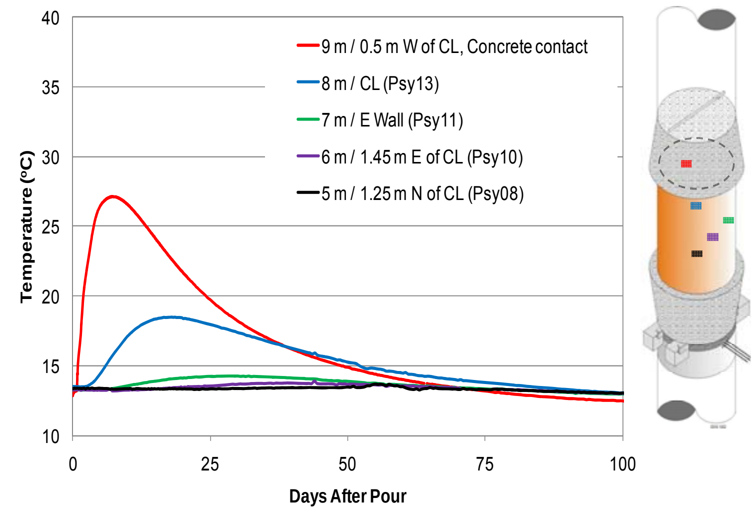
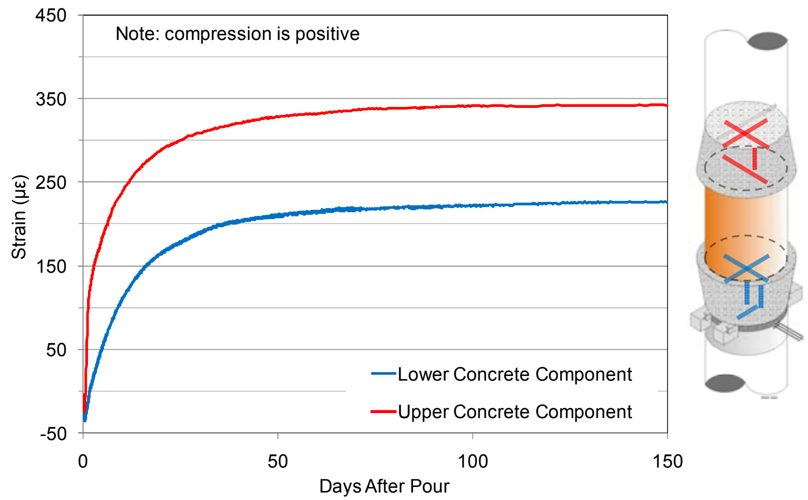


Figure 2. Temperature effects of concrete curing showing maximum temperature rise in the centre of the concrete components (left) and the adjacent clay-sand materials (right).



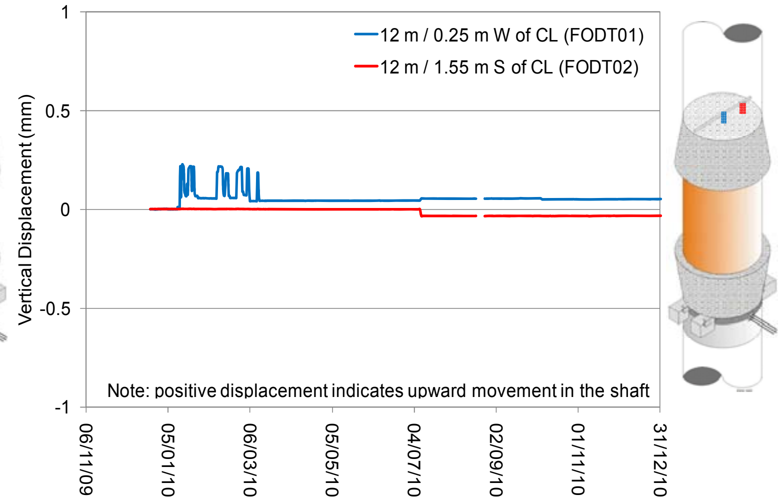


Figure 3. Displacements associated with concrete. Average linear strain of concrete components during curing (left) and vertical displacement of upper concrete surface (right).

The symbols used to identify sensor locations (Figures 2 through Figure 9) are: CL=centerline; W=west; E=east, N=north; S=south

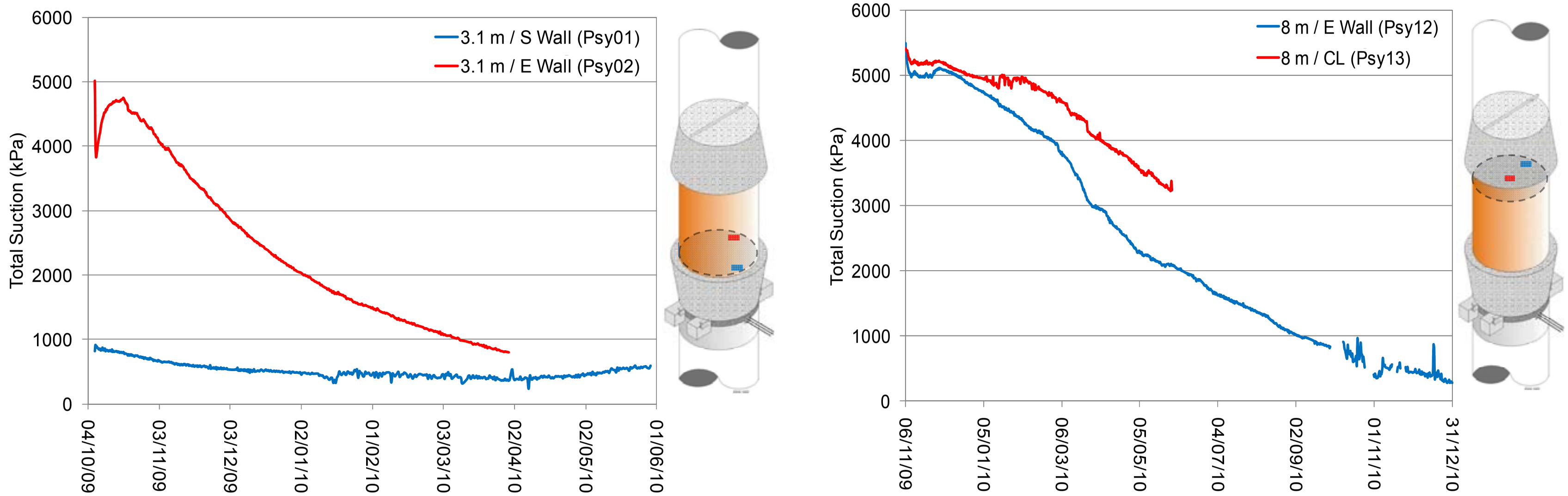


Figure 4. Examples of psychrometer readings.

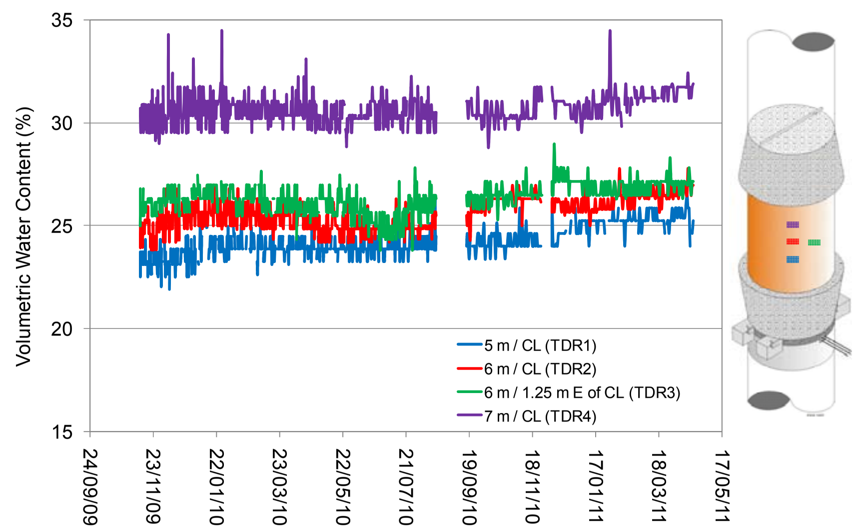


Figure 5. Water uptake in clay-sand as indicated by TDR probes.

Flooding of the access shaft is being monitored by a vibrating wire piezometer installed on the top surface of the shaft seal (Figure 6). Pumping of water from the top of the shaft seal was stopped on 11 March 2010 and flooding of the shaft above the seal up to the 240 Level began. It took approximately 110 days for the shaft volume above the seal (~ 476 m^3) to fill to the 240 Level. This equates to ~4.3 m^3/day, which is close to the ~4 m^3/day initially anticipated [1].

The transducers located at the rock-concrete interfaces shown in Figure 6 provide an indication of the hydraulic connection along the rock-concrete interface if interface grouting is not undertaken. Figure 6 shows that the upper concrete unit has an open interface between itself and the surrounding rock (pressures the same as for the flooded shaft). The lower concrete unit can therefore be expected to have a similar character and hence the pressures monitored in that region should be a reflection of the hydraulic pressures present in the shaft below the region occupied by the clay-sand mixture. One of the lower sensors is providing lower pressure readings than the others, perhaps the result of it being only poorly connected to the rock-concrete interface or encapsulated by concrete.

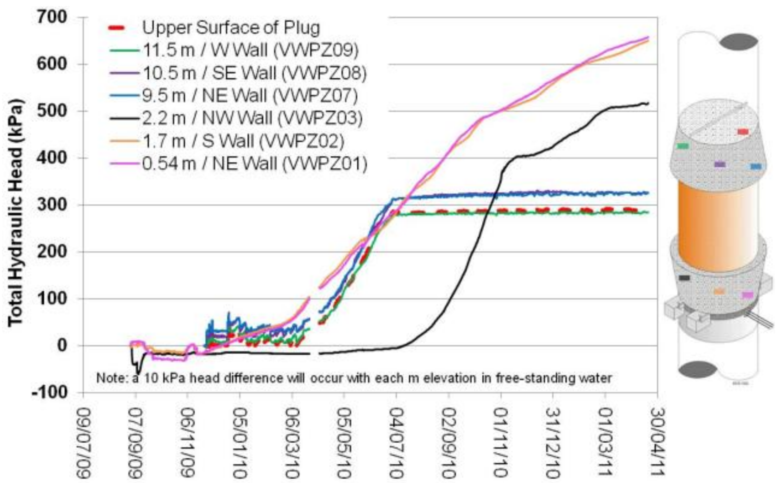


Figure 6. Hydraulic pressures in the shaft and at the rock-concrete interfaces.

The porewater pressure in the rock immediately adjacent to the shaft seal is measured at three horizontal distances into the rock (0.5 m, 1.0 m and 1.85 m) at a height of 4.5 m above the base of the clay-sand component. The sensors are located approximately 1.5 m above FZ2 in rock that is expected to be outside the fracture zone but may be influenced by the EDZ in the shaft wall. Figure 7 shows the data collected from these instruments, along with the water pressures at various locations in the shaft above and below the seal. For purposes of comparison, the data in Figure 7 are presented as total hydraulic heads with respect to the base of the shaft seal to account for the differing elevations of the instruments.

The porewater pressure in the clay-sand component is being monitored by 8 piezometers. The data collected by these instruments are shown in Figure 8, along with the shaft flooding measurement for comparison. Figure 8 shows that the porewater pressure in the majority of the clay-sand component has not substantially increased. A noteable exception to this trend is piezometer VWPZ06, which is close to the interface between the clay-concrete-rock contact and is reading ~250 kPa. It is therefore very close to the upper shaft water supply. VWPZ05 exhibits an unexpected cyclic pressure increase and decrease. This pattern can be attributed to the presence of trapped air at-or-near the concrete-clay contact. As water uptake by the clay-sand progresses, air migrates towards the core of the region filled with the clay-sand mixture and also upwards. The pressure in this region would gradually rise (pressure recorded is actually at least in part gas pressure rather than hydraulic). Once this pressure (or volume of gas) reached sufficient magnitude it forces its way upwards to the contact with the upper concrete and then vents out of the seal. The result is the drop in pressure recorded by the piezometers. This cycle would be repeated so long as there is gas/air movement upwards through the seal. By early 2011 this process seems to be decreasing in frequency and magnitude (see also the TPCs mounted in the seal, Figure 9).

The region surrounding the URL is being routinely monitored to observe the recovery of the regional groundwater conditions as the draw-down induced by the URL shafts decreases. Monitoring indicates that the regional groundwater pressures are already showing discernible recovery [5].

2.5 Total Pressures within clay-sand and at confinement boundaries

The total pressure within the clay-sand component is being monitored using a mixture of vibrating wire and fibre-optic total pressure sensors. They provide a measure of the forces that have been developed within the clay-sand and at the contact between it and the confining media (rock and concrete). The data from these instruments are shown in Figure 9 and Figure 10. The total vertical pressure at the centre of the clay-sand component (FOTPC02 in Figure 9) is less than the maximum pressures at the upper and lower concrete-clay interfaces, which is expected at this early stage in the evolution of the shaft seal. The outer edges of the clay-sand component are being acted on by a combination of hydraulic and swelling pressures, resulting in total pressures in excess of the hydraulic head recorded locally but still far lower than the conditions expected once the system has saturated and equilibrated.

All of the data from the TPCs plotted on Figure 9 and to a much lesser extent, the TPC's monitoring radial pressure at the clay-rock contact (Figure 10) show periodic spikes and sudden drops in pressure, especially in the upper-center region of the clay-sand component (FOTPC05). As noted previously, it is unlikely that these are the result of systemic interference affecting the sensors, since two of the TPCs are fibre optic and three are vibrating wire and hence represent two completely independent datalogging systems. Adjacent piezometers have also recorded spikes in readings. The magnitude of the spikes is greatest in the core of the seal (volume of gas isolated by saturating perimeter of clay-sand material and being compressed by the incoming water). The nature of the pressure releases indicates some form of degassing event where the excess pressure in the unsaturated region induces gas breakthrough near the top of the clay-sand component that then progresses along the clay-concrete and concrete-rock interfaces into the overlying water-filled shaft. Similar gas-breakthrough behaviour was observed in laboratory studies [8]. This type of behaviour has important implications with respect to the evolution of seals (speed of water saturation increased by reduction of gas-induced backpressure, as well as gas transport through bentonite-based barrier materials.

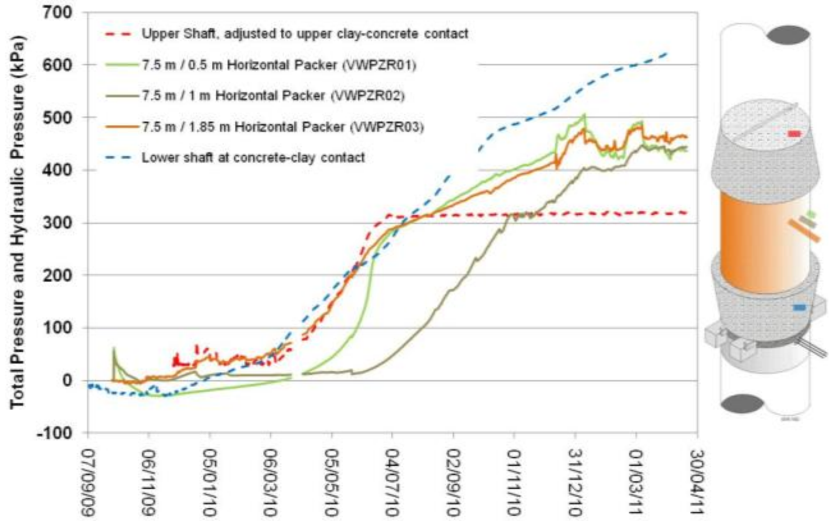


Figure 7. Hydraulic pressures in rock adjacent to the shaft seal.

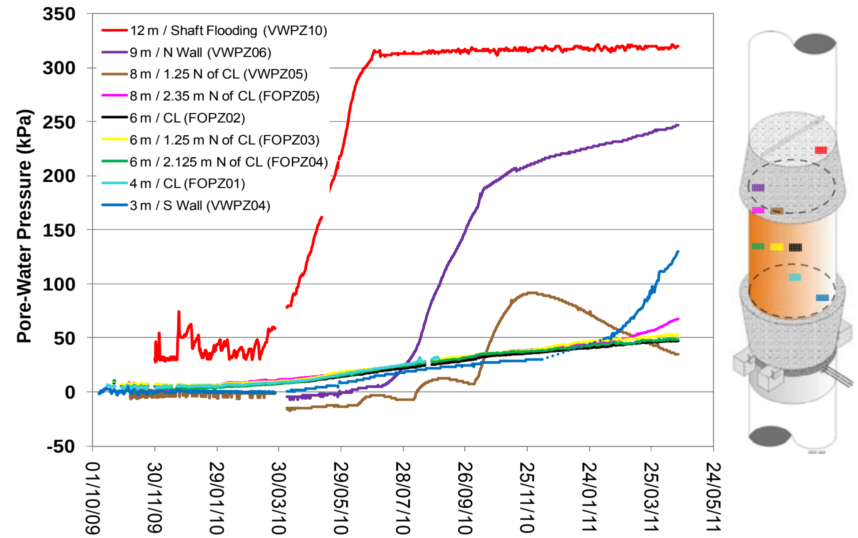


Figure 8. Porewater pressure in clay-sand mixture.

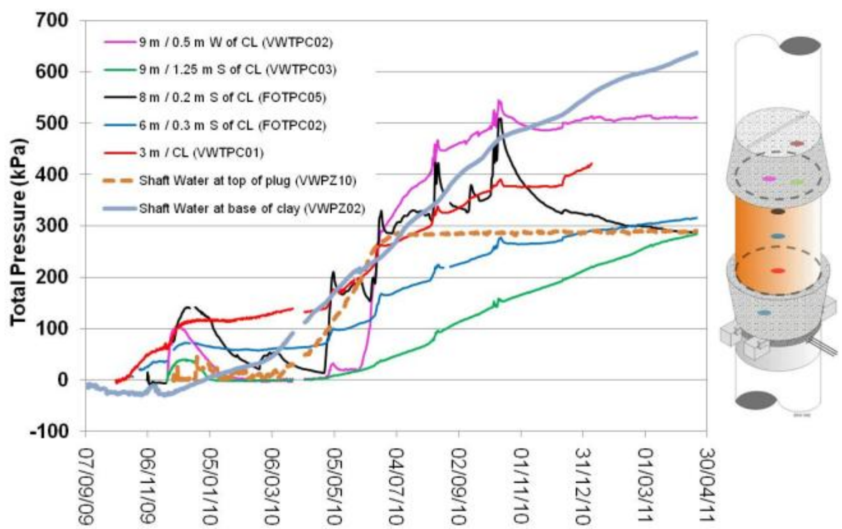


Figure 9. Total pressures along axis of sand-clay fill.

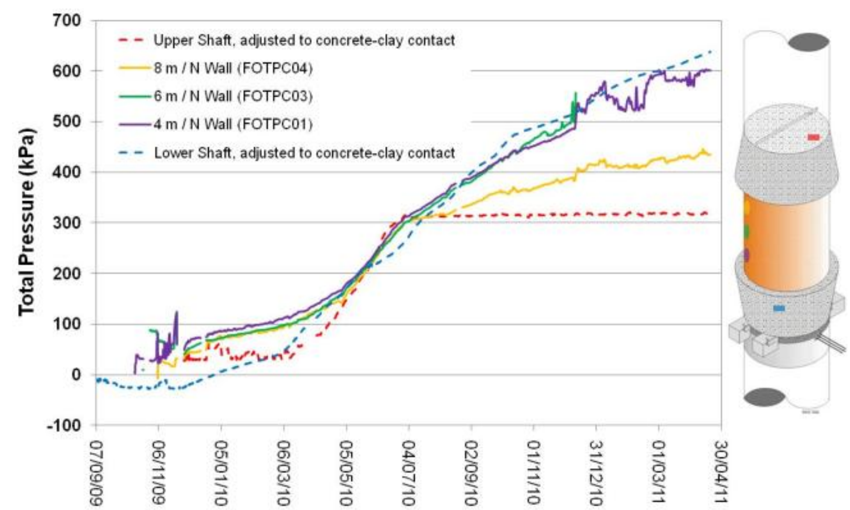


Figure 10. Total radial pressure at contact of clay-sand and rock

3. SUMMARY

The shaft seal at AECL's URL was successfully installed at a depth of 275 m at the intersection of the access shaft and a hydraulically active fracture zone. The seal will assist in limiting the mixing of deeper saline groundwater with shallower less-saline groundwater. This work has demonstrated that a full-scale repository-like shaft seal can be installed at depth in a vertical shaft using conventional construction techniques.

Instrumentation for observing the T-H-M evolution of the shaft seal has been successfully installed and is being monitored from the surface using a variety of datalogging techniques. It has been shown that a shaft seal installed at a depth approaching 275 m can be effectively monitored using mostly conventional instrumentation technologies. The instrumentation is monitoring the T-H-M evolution of a shaft seal and will allow the future performance of the seal to be evaluated and modelled using realistic parameters.

The shaft seal is still in its early stages of evolution with respect to wetting, swelling and development of hydraulic pressures. The system is being saturated from both ends via the rock-concrete interfaces as well as from the intersecting fracture and adjacent rock. The result of this type of water uptake is an encapsulation process where water is moving into the clay-sand portion of the seal, trapping and compressing air. This air is apparently escaping the seal by a series of short-duration venting events. Moisture sensors installed within the regions filled with clay-sand indicate the presence of a saturated perimeter and an as-yet unsaturated core.

The interpretations presented in this paper are based on the results of a very short period of monitoring (~18 months) of a system that is still in the early stages of its evolution. With ongoing monitoring the system the interactions between the various components will become clearer and a better understanding of what is occurring will be possible. To this end, a 3-year extension to the monitoring program has been agreed to by all of the participants (NWMO, ANDRA, SKB and Posiva) and monitoring will continue through to at least the end of 2013.

ACKNOWLEDGEMENTS

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