The Enhanced Sealing Project: Instrumentation and Monitoring of a Full-Scale Shaft Seal

B.E. Holowick
Atomic Energy of Canada Limited, Pinawa, Manitoba, Canada

ABSTRACT
Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory (URL), located 150 km northeast of Winnipeg, Manitoba, is currently being decommissioned and its underground facilities permanently closed. As part of the URL closure, shaft seals have been installed at a depth of approximately 275 m at the intersections of the main shaft and ventilation raise with a deep fracture zone. The installation of these seals provides a unique opportunity to study the behaviour of a functional full-scale shaft seal. The Enhanced Sealing Project arose from this opportunity and consists of the installation and monitoring of a suite of sixty eight (68) instruments installed in the main shaft seal.

RÉSUMÉ
Le Laboratoire de recherches souterrain (LRS) d'Énergie atomique du Canada limitée (EACL), qui se trouve à 150 km au nord-est de Winnipeg (Manitoba), est présentement en cours de déclassement et ses installations souterraines seront fermées définitivement. Lors de la fermeture du LRS, on a installé dans les puits des joints d'étanchéité à une profondeur d'environ 275 m aux points de croisement du puits principal et du puits d'aération avec une zone de fracture profonde. L'installation de ces joints offre une occasion unique d'étudier le comportement d'un joint d'étanchéité de grandeur nature pour les puits. Le Projet d'amélioration de l'étanchéité résulte de cette possibilité; il consiste à installer et à surveiller un ensemble de soixante-huit (68) instruments installés sur le joint d'étanchéité du puits principal.

1 INTRODUCTION

Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory (URL) was constructed as a facility to study concepts for the long term isolation of Canada's used nuclear fuel in a deep geologic repository (DGR). The URL is located in the granitic Lac du Bonnet batholith in south-eastern Manitoba, 150 km northeast of Winnipeg. Excavation of the URL began in 1982, and numerous experiments have been conducted since 1983 including studies of rock mass response to excavation, full-scale buffer experiments and full-scale sealing experiments. The URL provided much of the technical information used to develop the DGR concept submitted by AECL to the Government of Canada (AECL 1994).

In 2003 the decision was made to close the underground portion of the URL and permanently seal its main shaft (access shaft) and ventilation raise (ventilation shaft). As part of the URL closure project, full-scale shaft seals were installed at the intersections of the main shaft and ventilation raise with a low-dipping ancient thrust fault (Figure 1). This thrust fault, known as Fracture Zone 2 (FZ2), is the main pathway for groundwater movement in the vicinity of the URL and defines the boundary between deeper more saline groundwater and shallower less saline groundwater. The purpose of the shaft seals is to limit the potential mixing of these two groundwater regimes and return the site to its predevelopment state.

Construction of the shaft seals is part of the Nuclear Legacy Liabilities Program (NLLP) and was funded by Natural Resources Canada (NRCan). The NLLP monitoring program only provides basic hydrogeological monitoring of the surrounding rock mass. The Enhanced Sealing Project (ESP) arose from the recognition of a unique opportunity to study the hydro-mechanical evolution of a full-scale repository-like shaft seal installed in a well characterized rock mass. As a result of this opportunity, four nuclear waste management organizations (Canada's Nuclear Waste Management Organization (NWMO), France's Agence Nationale pour la gestion des Dechets Radioactifs (ANDRA), Finland's Posiva Oy and Sweden's Svensk Kärnbränslehanertring AB (SKB)) partnered to support a project to enhance monitoring of the NRCan-funded construction of the main shaft seal through the installation of a suite of sixty eight (68) monitoring instruments. The ventilation raise seal contains no instrumentation and is not being monitored.

2 THE MAIN SHAFT SEAL: GEOMETRY, MATERIALS AND CONSTRUCTION

2.1 Shaft Seal Geometry

The main shaft seal is installed at a depth of 275 m at the intersection of the main shaft and FZ2. The shaft seal is a composite type, and consists of a 6-m-thick swelling bentonite-sand (clay) component rigidly confined between two 3-m-thick conical frustum shaped concrete components (Figure 2). The concrete components are keyed 0.5 m into the shaft wall to anchor them in place and restrain the bentonite-sand as it hydrates and swells. The main shaft is circular and varies from 4.8 m to 5.0 m in diameter in the location of the shaft seal. This irregularity in diameter is due to the drill-and-blast construction of the shaft.

Note that the bentonite-sand component provides all of the sealing capabilities of the shaft seal, and FZ2 is exposed entirely within it. The concrete components of the seal are not watertight along their perimeter, and only serve to support and restrain the swelling bentonite-sand.

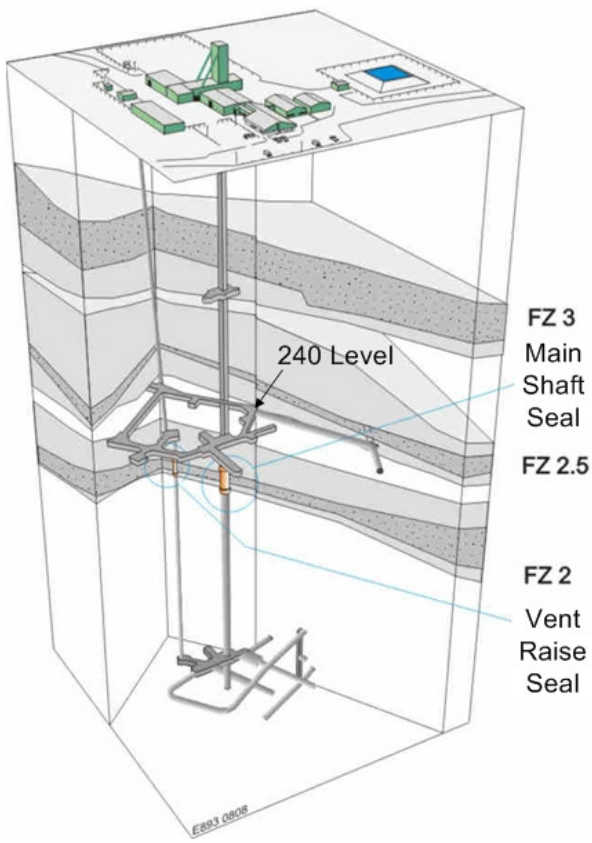

Figure 1. Layout of the URL and location of shaft seals

2.2 Shaft Seal Materials and Construction

Bentonite clay was used in the construction of the shaft seal due to its very low permeability and swelling capabilities. The swelling behaviour of bentonite-based materials leads to self-sealing and self-healing properties that are very desirable in shaft seals. As the bentonite clay hydrates and swells, while being rigidly confined by the concrete and host rock, it induces swelling pressures that improve its sealing performance by i) creating a water-tight seal at the clay-rock interface, ii) helping to seal circumferential fractures in close proximity to the shaft, and iii) possibly causing self-injection of the bentonite into intersecting fractures (Pusch et al. 1987).

The bentonite-sand material used in the shaft seal is a mixture, by mass, of 40% Wyoming bentonite and 60% washed quartz sand. The bentonite-sand was compacted *in situ* in 5-cm-thick lifts using two electric vibratory rammers, and took approximately one month to install. It is installed at an average dry density of 1810 kg/m^3, with an average a water content of 12.1%. The water content of the blended bentonite-sand material was suitable for compaction, and moisture conditioning was not required. The expected swelling pressure of the bentonite-sand material is 1250 kPa with fresh water as the pore-fluid and approximately 550 kPa with moderately saline water.

The upper and lower concrete components are constructed from low heat (of hydration) high performance concrete (LHHPC). The LHHPC concrete mix design was created by AECL and is the same mix that was used in the Tunnel Sealing Experiment conducted at the URL (Chandler et al. 2002). The low heat of hydration is desirable when pouring high mass structures and will minimize the effects of high temperature on the seal components, the host rock and the bentonite-sand barrier. The LHHPC also has a low pH (~9.8) that will reduce interactions affecting the swelling capability of the adjacent bentonite.

The upper concrete component contains no reinforcing bar, whereas the lower concrete component is reinforced to carry the load of all overlying materials, including a 270 m column of water.

After the shaft seals were constructed the URL was left to passively flood. The estimated time until the URL is fully flooded is 10 to 14 years, assuming an average influx of 3 m^3 to 4 m^3 per day (Dixon et al. 2009).

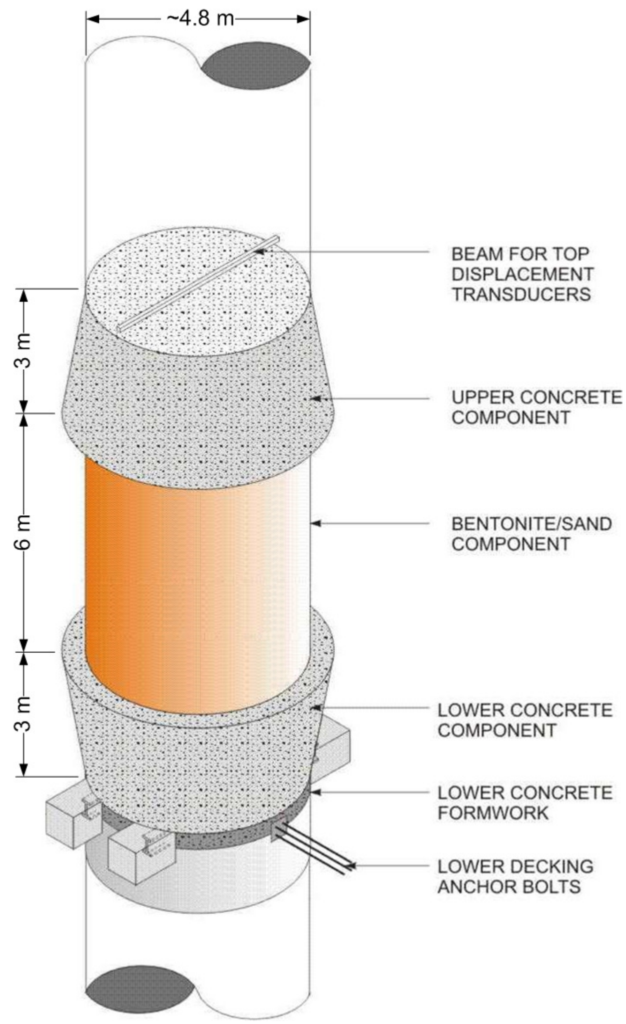

Figure 2. Schematic of the main shaft seal

3 INSTRUMENTATION INSTALLATION

The instrumentation arrangement in the main shaft seal is designed to monitor a set of key parameters that allow the evolution of the seal to be observed. The parameters of interest in the concrete components include strain, temperature, applied total pressure and hydraulic pressure at the concrete-rock interfaces. The parameters being monitored in the bentonite-sand component are water content, soil suction, swelling pressure and pore-water pressure. Pore-water pressure in the near-field rock and the hydraulic head above the shaft seal are being measured for groundwater recharge and shaft flooding. Vertical displacement of the top surface of the shaft seal is also monitored.

The shaft seal instrumentation is required to be monitored remotely from the surface, since access to the shaft seal after the URL closure will not be possible. Therefore instruments capable of operating with very long cables (350 m), such as vibrating wire and fibre optic based instruments, were used whenever possible. However, two dataloggers had to be installed underground to monitor the instruments with cables not long enough to directly reach the surface. One of the underground dataloggers monitors the psychrometers and thermocouples, and will lose functionality once it is inundated by water during shaft flooding. The other underground datalogger monitors the time domain reflectometry (TDR) probes and is encased in a watertight pressure resistant container that will allow it to operate after the 240 Level has flooded; this greatly increases its expected service life.

3.1 Instruments in the Lower Concrete Component

The lower concrete component contains internal fibre optic strain gauges and thermocouples, as well as vibrating wire piezometers at the concrete-rock interface. Vibrating wire instruments were used in the concrete components because they contain thermistors that provided useful temperature data during concrete hydration. The lower concrete component has a dense pattern of rebar (Figure 3) that provided mounting locations for the instruments, which were mostly installed as the rebar installation progressed. However, the denseness of the rebar layout also made it difficult to install some instruments, since it was hard to reach the desired mounting locations. In these situations mechanical reach extenders (grabbers) were used to position and mount the instruments. The two vertically oriented fibre optic strain gauges were the most difficult to install, since they needed to be mounted after the rebar installation was complete.

The filter tips of the vibrating wire piezometers at the concrete-rock interface were wrapped with non-woven geotextile and installed in direct contact with the rock wall. The geotextile prevented concrete from encasing the sensing tip of the instruments, and essentially increased the size of the piezometers' filters allowing them to more easily intersect the concrete-rock interface.

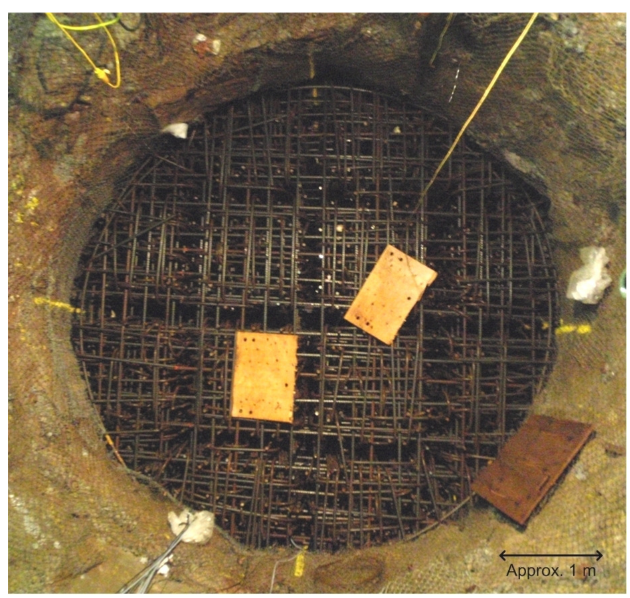

Figure 3. Top view of lower concrete component rebar

3.2 Instruments in the Bentonite-Sand Component

The bentonite-sand component contains vibrating wire and fibre optic piezometers and total pressures cells (TPC), psychrometers, and TDR probes. The piezometers and TPCs are installed at the interior and perimeter of the component, and measure internal and interface hydraulic and total pressures. The psychrometers and TDRs, which measure soil suction and volumetric water content, are installed throughout the volume of the component. Soil suction is used as an indicator of the stage of saturation of the material. The TDRs are located closer to the centre of the mass, where saturation will occur last, and the psychrometers are closer to the perimeter where saturation should occur more rapidly. This was done since the datalogger for the psychrometers will eventually flood and is not expected to last as long as the watertight TDR datalogger.

The installation of the instruments in the bentonite-sand component was very simple. The instruments were installed in layers at 1 m vertical intervals throughout the component. Prior to the installation of each instrument group the bentonite-sand was installed and compacted to an elevation 20 cm above the instrumentation level. To install smaller instruments, such as psychrometers (1 cm Ø) and piezometers (2.5 cm Ø), holes were drilled down to the required elevation and the instruments inserted and backfilled (Figure 4). For larger instruments, like TDR probes (40 cm long) and TPCs (23 cm Ø pressure cell), holes were manually excavated, the instruments inserted, then backfilled and compacted to the proper density either manually or using an electric impact hammer (Figure 5). These installation methods ensured that compacted material of the proper density surrounded the instruments, and also provided a 20-cm-thick layer of protection above them during the compaction of subsequent lifts.

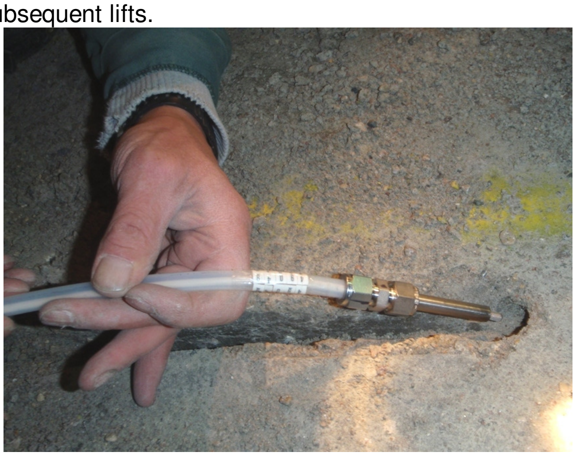

Figure 4. Installing a psychrometer in the bentonite-sand

The installation of the TDR probes was the most complex of all the instruments installed in the bentonite-sand component. The TDRs have two 7.5 mm diameter probe rods that are 30 cm long. The probe rods are required to be parallel and in contact with the surrounding material once installed. This meant that a high quality installation using manual drilling or compaction would have been very difficult. Therefore, prior to installation each TDR probe was inserted into a pre-compacted bentonite-sand brick with holes drilled in it. The holes for the probe rods were drilled on a lathe so they were exactly parallel and snugly fit the TDR probe rods. The bricks were manufactured to the same density as the material in the shaft seal. Figure 5 shows a TDR prode installation.

3.3 Instruments in the Upper Concrete Component

The upper concrete component contains internal fibre optic strain gauges and thermocouples, as well as vibrating wire piezometers and TPCs at the concrete-rock interface. There are also two fibre optic displacement transducers (FODT) and a vibrating wire piezometer installed on top of the concrete to monitor vertical displacement and shaft flooding.

Unlike the lower concrete component, the upper concrete component does not contain any rebar. Therefore the instruments installed at the interior of the concrete had to be supported in place before the concrete was poured. This was done by stringing 1/4" steel cables across the shaft in the locations where instruments were to be placed, then attaching the instruments to the cables (Figures 6). These support cables were held in place using I-bolts and turnbuckles anchored to the rock wall. The support cables could be positioned very accurately, and allowed the instruments to be installed in essentially the exact locations specified in the instrumentation plan (+/- 1 cm). A total of four horizontal support cables and two vertical support cables were required to mount the instruments. The vertical support cables were installed by spanning them across three horizontal cables and clipping them in place. The support cables securely held the instruments in place during the upper concrete pour (Figure 7).

Figure 5. Installing a TDR probe in a pre-compacted bentonite-sand brick (top), TDR probe (bottom)

Figure 6. Support cables during instrument installation in the upper concrete component

Figure 7. Support cables during the upper concrete pour

The TPCs and piezometers located at the concrete-rock interface were installed by anchoring them to the shaft wall using rock bolts. Similarly to the lower concrete component, the piezometer filter tips were wrapped with non-woven geotextile prior to installation. Also, the TPCs had a globule of hydraulic cement placed behind them and were pressed into it before being bolted to the shaft wall. This ensured that the TPC pressure pads were in direct contact with the rock wall.

The FODTs measuring vertical movement of the upper concrete component are mounted to a rigid beam located 0.3 m above the shaft seal (Figure 8). The beam is 4" box steel and spans the width of the shaft. The tips of the FODTs' plungers are attached to the concrete surface using drop-in concrete anchors and steel tabs (Figure 9). A wooden box was constructed over the FODT mounting beam to protect the instruments from debris that is expected to accumulate on top of the shaft seal, the box will also ensure that no external loading is applied to the beam.

3.4 Instruments in the Adjacent Rock

There are three mechanical packers installed at 0.5 m, 1.0 m and 1.85 m horizontal depths in the rock adjacent to the bentonite-sand component. These packers have vibrating wire piezometers attached to them that measure the rock pore-water pressure in the isolated zone at the end of each packer. The packers and piezometers will provide information regarding the interaction of the swelling bentonite-sand and the near field rock.

4 DATALOGGERS

4.1 Surface Dataloggers

As previously stated, instruments capable of operating with 350 m of cable were used whenever possible. This allowed their dataloggers to be located on the surface, which is extremely beneficial in the event of a datalogger malfunction. All of the piezometers, TPCs, strain gauges and FODTs have dataloggers located on the surface.

Figure 8. FODT mounting beam above the shaft seal

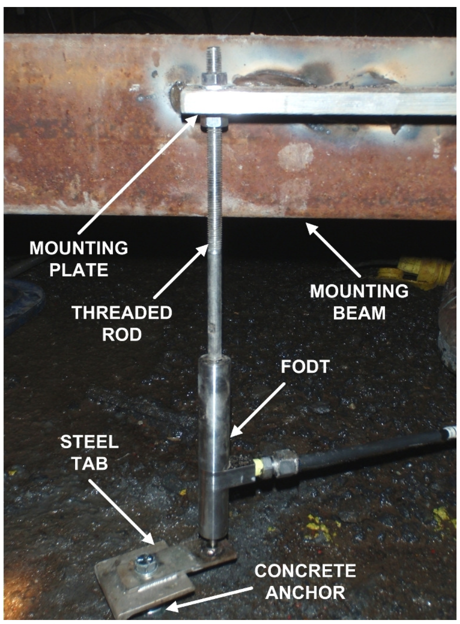

Figure 9. FODT installation detail

4.2 Underground Dataloggers

Some of the instrument technologies were limited to 50 m to 60 m long cables; these include the thermocouples, psychrometers and TDRs. Beyond this length line losses would severely degrade their performance and accuracy. Therefore dataloggers for these instruments needed to be located underground within 50 m of the shaft seal. Fortunately, the 240 Level of the URL is only 30 m from the top of the shaft seal and provided a convenient site to locate these dataloggers.

The datalogger monitoring the thermocouples and psychrometers is “sacrificial” and will lose functionality once shaft flooding has reached it. This datalogger, and its required communications devices, are mounted on a shelf located 2.75 m above the floor of the 240 Level (Figure 10). Mounting the datalogger at this height should allow it to operate for approximately 7 years before it is inundated by water from natural shaft flooding (Dixon et al. 2009). It is estimated that the useful life of the instruments monitored by this datalogger will be finished when it floods. The datalogger has a dedicated power line and fibre optic communications line that run from the surface to the 240 Level.

The TDR probes are also monitored by a datalogger located on the 240 Level. It is installed in a watertight pressure resistant container that should allow it to operate under 240 m of head after the shaft has fully flood. The TDR datalogger also has a dedicated power and communications line running directly to the surface.

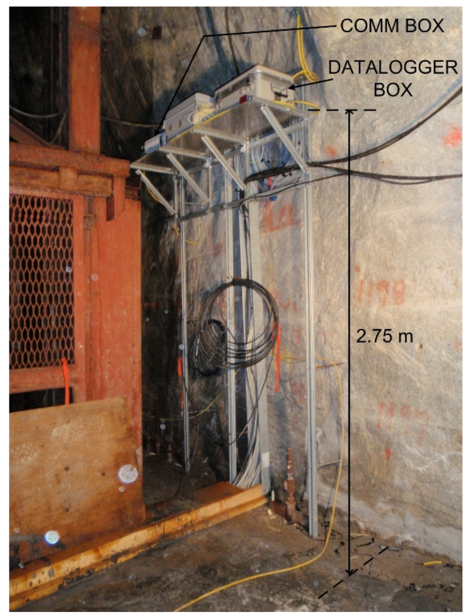

Figure 10. Sacrificial datalogger located on the 240 Level

5 INITIAL MONITORING DATA

5.1 Concrete Components

At the preparation of this paper (April 2010), the shrinkage and temperature of the concrete components during hydration has successfully been monitored. The maximum recorded temperature increase during hydration of the lower and upper concrete components was 16.0°C and 18.6°C, respectively. These values are comparable to those observed during AECL’s Tunnel Sealing Experiment (Chandler et al. 2002) and are close to the expected values for this concrete mix (Gray and Shenton 1998). Shrinkage from the hydration of both concrete components is complete. The shrinkage strain was observed to be essential isotropic in both components, with the upper component exhibiting approximately 50% more shrinkage compared to the lower concrete component (Figure 11). This difference in shrinkage is the result of the lower component being reinforced and the upper component being un-reinforced. These shrinkage strains result in a 0.6 mm to 0.9 mm gap forming around the perimeter of the concrete components, and explain why the concrete-rock interface is not watertight.

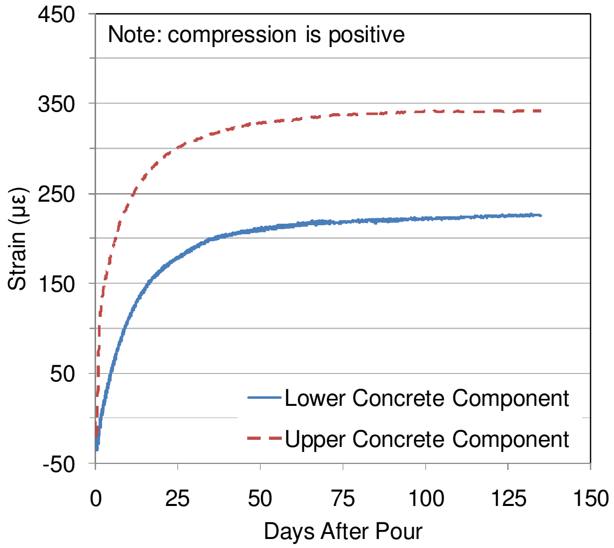

Figure 11. Average strain of the concrete components

The two TPCs located at the upper concrete-clay interface showed an initial increase in vertical pressure following the concrete pour, then dropped to zero as the concrete cured (Figure 12). This is an indication that the concrete shrank away from the bentonite-sand during hydration and is completely self supporting. As the bentonite-sand continues to hydrate it will swell and begin reacting on the upper concrete component.

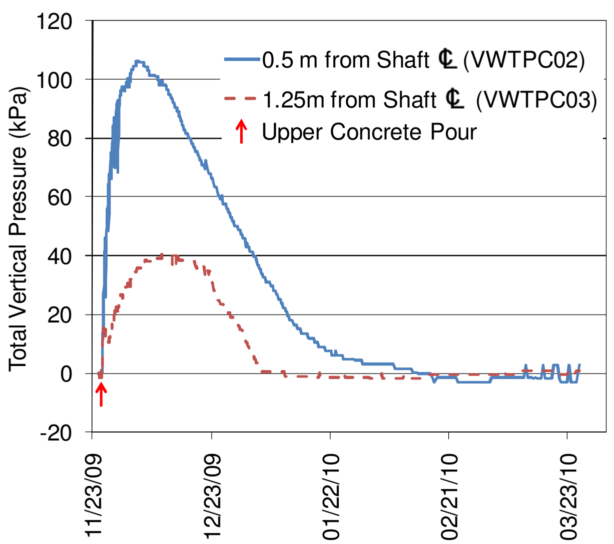

Figure 12. Total vertical pressure at the upper concrete-clay interface following the upper concrete pour

Hydraulic pressure readings from piezometers at three elevations of the concrete-rock interface of the upper concrete component are shown in Figure 13. The pressures measured by the interface piezometers mirror the response of the piezometer located on top of the shaft seal, indicating that the concrete-rock interface is highly permeable. The undulating pattern of the hydraulic pressures is the result of successive flooding and pumping of water from the top of the shaft seal.

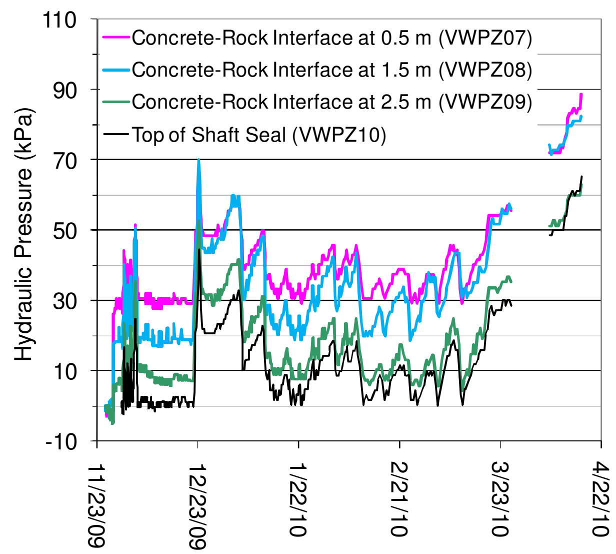

Figure 13. Hydraulic pressures at the upper concrete-rock interface and above the upper concrete component

5.2 Bentonite-Sand Component

At the preparation of this paper, the initial saturation of the bentonite-sand component is underway. The psychrometers located near the lower edges of the bentonite-sand component are showing a gradual reduction in soil suction, indicating that the material is wetting. While the psychrometers located in the upper half of the component are showing dryer conditions (Figure 14). The pattern of soil suction agrees with the points of water inflow observed during shaft seal construction, as most of the inflow occurred at or below FZ2 in the bottom half of the bentonite-sand component. The TDR probes located near the centre of the bentonite-sand component are indicating little to no change in water content thus far. When viewing Figure 14 note that the bentonite-sand component has a total height of 6 m.

The TPCs positioned in and around the bentonite-sand component are showing only minor increases in pressure, indicating that no significant swelling has yet occurred in the bentonite-sand.

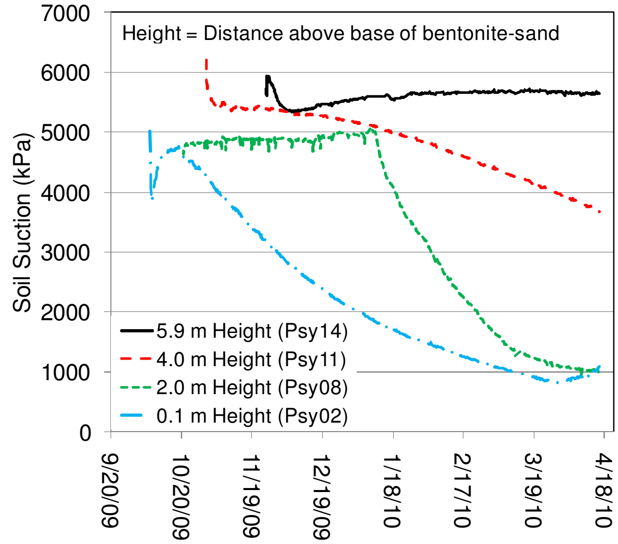

Figure 14. Soil suction in the bentonite-sand component

6 SUMMARY

Two shaft seals have been successfully installed at 275 m depth as part of the decommissioning and closure of AECL's URL. These seals were installed to limit the potential mixing of deeper more saline groundwater with shallower less saline groundwater.

Through an international partnership involving four nuclear waste management organizations (Canada's Nuclear Waste Management Organization (NWMO), France's Agence Nationale pour la gestion des Dechets Radioactifs (ANDRA), Finland's Posiva Oy and Sweden's Svensk Kärnbränslehanertring AB (SKB)), the monitoring of the main shaft seal was enhanced by installing instrumentation for remote monitoring of the seal's hydro-mechanical evolution following closure of the URL. This instrumentation and monitoring is known as the ESP.

The ESP required surface monitoring of instruments installed at 275 m depth. This obstacle was overcome by using a combination of instruments capable of functioning with 350 m long cables, installing a sacrificial datalogger at depth, and installing a watertight pressure resistant datalogger at depth.

So far the ESP has provided data regarding the curing of both the upper and lower concrete components of the shaft seal. The instruments installed in the swelling bentonite-sand component are showing the early stages of hydration. As the bentonite-sand continues to take on water and swell, the instrumentation will provide valuable data regarding the evolution of a full-scale repository-like shaft seal.

Acknowledgements

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The significant contribution of the URL's instrumentation technicians, Frank Johnston, Glen Snider and Dennis Soloway, is also acknowledged.

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