

**The Enhanced Sealing Project, Monitoring a Full-Scale Shaft Seal at  
Canada's Underground Research Laboratory (2009-2015) – 16070**

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**ABSTRACT**

A full-scale shaft seal was designed and installed in the 5-m-diameter main shaft at Canada's Underground Research Laboratory (URL) in 2009. Located where the main shaft intersects a water-bearing fracture zone at a depth of approximately 273 m, a 6-m-thick clay component was sandwiched between two 3-m-thick concrete components. The clay component was 40:60 mixture of bentonite and quartz/feldspar sand and spans approximately 1 m beyond the maximum identified vertical extent of the fracture zone. Its purpose is to limit the mixing of saline groundwater from the deeper region with the fresher, near-surface groundwater. Its construction was part of Canada's Nuclear Legacy Liabilities Program (NLLP). The 1<sup>st</sup> phase of the Enhanced Sealing Project (ESP), a jointly-funded Research, Development & Demonstration (RD&D) project was started in 2009 to monitor the saturation of the shaft seal until the end of 2013. The 2<sup>nd</sup> phase, extended monitoring of the ESP is supported by Posiva (Finland), Andra (France) and CNL (Canada) and this will run until the end of 2016. The slow evolution of the seal and its surroundings and complete removal of the surface facilities at the URL site in 2014, has meant that the ESP monitoring has evolved to a stand-alone, lower frequency data collection program. Information gained from the ESP monitoring is applicable to support the development of sealing technology to safely close a deep geological repository for the permanent disposal of radioactive wastes.

**BACKGROUND**

A deep geological repository (DGR) for final disposal of high level radioactive wastes is one of the important components of the back-end of the nuclear fuel cycle [1]. A safe and acceptable end point will be required, whether or not additional steps such as reprocessing, transmutation, and advanced reactors are considered in the nuclear fuel cycle. Currently, a DGR has been recognized as the preferred option for the ultimate end point for high-activity, long-lived radioactive wastes [2]. At depths of hundreds meters, suitable rock formations will work in concert with multiple engineered barrier systems, including the container, bentonite- and concrete-based materials to protect the disposal facility from human interference and from natural processes such as earthquakes or climate changes [3].

Specifically, at the end of a DGR's operation, multiple engineered barrier systems will need to be installed in the access shafts (and ramps if present) in order permanently seal the facility [3]. Closure of an actual DGR is not anticipated to occur for more than

100 years from now (i.e., 2120's) (Posiva (Finland)[4]). Consequently, it is important to demonstrate both long-term performance of such seals and also how preservation of knowledge related to the safe closure of the DGR can be accomplished.

Due to the long-lived characteristics of radioactive waste, a DGR requires safe performance over extremely long time spans. In Canada, extensive multidisciplinary Research, Development, and Demonstration (RD&D) projects have been conducted at the Underground Research Laboratory (URL) near Pinawa, Manitoba, Canada to support the development of a safe DGR. Most of this work was done between 1980 and 2003 as national or international jointly funded projects. In 2003 the decision was made to permanently close the Canadian URL. During the 6-year long stepwise decommissioning and closure of the underground facility, seals were installed in the shafts. This paper presents the status and monitoring results of the Enhanced Sealing Project (ESP) in which a full-scale shaft seal at the URL is being monitored. This monitoring program is the last ongoing RD&D project at the URL.

With complete demolition of the URL's surface facilities in 2014 and continuing organizational and personnel changes, the ESP represents an excellent example of the importance and challenges to preserving knowledge over the longer-term. Additionally, other projects completed at the URL provided a foundation for design and construction of the ESP and have potential applications to support safe development of a DGR in the future. A paper discussing lessons learned from Canada's URL (1980-2015) has also been prepared [5].

### **ENHANCED SEALING PROJECT (ESP)**

As part of URL closure, the construction of two shaft seals was funded by Canada's Nuclear Legacies Liability Program (NLLP). Monitoring of the full-scale main shaft seal during the recovery of the regional groundwater regime can be used to support the development of a DGR by demonstrating successful construction and operation of the seal. The 1<sup>st</sup> phase of the Enhanced Sealing Project (ESP) was developed in 2009 by AECL (Canada) and funded by the NWMO (Canada), SKB (Sweden), Posiva (Finland) and Andra (France). This phase involved monitoring of the initial Thermal-Hydraulic-Mechanical (THM) evolution of the seal in the main shaft over the period 2009 to 2013. The results of this initial phase have been presented in various reports and papers [6],[7],[8],[9],[10],[11],[12].

The ESP data collected to the end of 2013 indicated that extension of ESP monitoring was required in order to capture enough information to allow for longer-term extrapolation of system evolution [12]. Long-term monitoring to allow the seal to fully saturate and for the URL shaft to flood above the 240 level excavation was desirable. Reduced operating budget, organizational changes and complete demolition of the URL infrastructure were some of the challenges to continuation of the shaft seal monitoring beyond 2013. Slow ongoing evolution and saturation of the seal and its surroundings allowed for a stand-alone, lower frequency manual data collection program to be initiated. The ongoing 2<sup>nd</sup> phase of the ESP is being supported by Posiva (Finland), Andra (France) and CNL (Canada) and will monitor the shaft seal to the end of 2016.

The as-built ESP seal is illustrated in Fig. 1. As part of URL closure, two seals were designed and installed at the points where the main shaft and vent shaft intersect a water-bearing, low-angle thrust fault (Fracture Zone 2 (FZ2)), at a depth of approximately 275 m (Fig. 1). The seals were designed to limit mixing of saline groundwater below FZ2 with fresh groundwater above FZ2. These seals were designed to function in the same manner as a shaft seal in an actual DGR (i.e., limiting upwards groundwater movement), although no radioactive wastes were present in the URL.

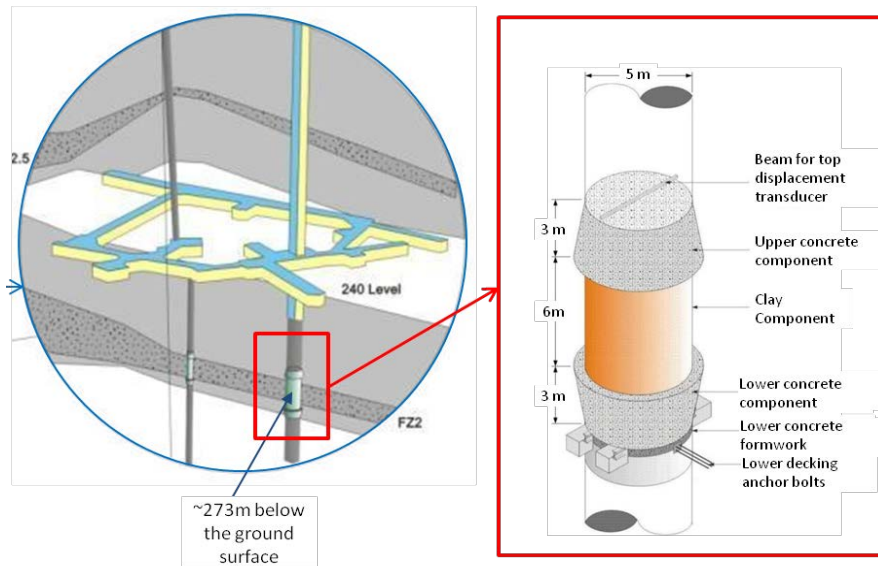


Fig. 1. The Enhanced Sealing Project (ESP)'s Full-Scale Clay-Concrete Shaft Seal

The seal in the main shaft has a diameter of approximately 5 m and consists of a 6-m-thick clay component sandwiched between 3-m-thick upper and lower concrete components. The concrete components are keyed into the granitic rock to a maximum depth of approximately 0.5 m (Fig. 1). The clay component spans the fracture zone and extends approximately 1 m beyond the maximum identified extent of the fracture zone at either end. The clay component is an in situ compacted mixture of bentonite clay (40% dry mass) and quartz/feldspar sand (60% dry mass) compacted in situ to an as-placed dry density of approximately  $1810 \text{ kg/m}^3$ . The clay component provides hydraulic sealing capability and assists in limiting saline groundwater transport from the deeper regime through the seal. The concrete components provide mechanical support and confinement to the swelling clay component and are not expected to serve a hydraulic sealing function. More details regarding the design and construction have been provided in [6] and [10]. The concrete components consist of a heavily-reinforced lower segment and an unreinforced upper segment. The concrete is a low-heat, low pH and high strength concrete mixture.

### SENSORS AND MONITORING SYSTEMS

One hundred (100) sensors were installed in 2009 at various locations in the clay, concrete and the host rock in order to monitor Thermal-Hydraulic-Mechanical (THM) responses. TABLE I summarizes the types of sensors, parameters being measured and the number of sensors installed in the shaft seal. Sensor installation and functionality were detailed in [6], [9], and [10]. Instrumentation consists of vibrating wire (VW) sensors, fibre optic (FO) sensors and time domain reflectometer (TDR) sensors. These sensors measure temperature, hydraulic pressure, total pressure, displacements, concrete strains and clay saturation in terms of total suction and volumetric water content. The majority of these sensors (i.e., 64 sensors) were intended only to capture the early stages of seal evolution (e.g. temperature, concrete strain, and water content near the perimeters of the clay component (psychrometers)). Most of these accomplished their purpose during the 1<sup>st</sup> phase of the ESP before ceasing to function or providing no further useful information.



Fig. 2. ESP Monitoring Enclosure Near the URL Concrete Shaft Cap

During the 1<sup>st</sup> phase of the ESP (2009 to 2013), automated data logging monitoring systems were used to record the readings provided by the ESP sensors. These data logging systems were located in two dedicated rooms at the URL surface facility (Fig. 2). They were connected to AECL's network and regularly backed up. The data up to the end of 2012 have been reported previously in [6], [8], and [9]. The data up to the

end of 2014 have been reported in detail in annual technical documents available to participating funding partners.

TABLE I. Sensors Installed in the Enhanced Sealing Project

Sensor Type	Parameter Measured	Number of Sensors	
		Installed	2 <sup>nd</sup> Phase of ESP (2014-2016)
Psychrometers (Psy)	Relative humidity	14	0
Thermocouple in the Psychrometers	Temperature	14	0
Thermistors (Ct)	Temperature	10	0
Fibre Optic Strain Sensors (FOSC)	Concrete Strain	10	0
Fibre Optic Displacement Transducers (FODT)	Vertical displacement	2	2
Fibre Optic Total Pressure Cells (FOTPC)	Contact Pressure	5	5
Fibre Optic Piezometer (FOPZ)	Hydraulic Pressure	5	5
Vibrating Wire Piezometers (VWPZ, VWPZR)	Hydraulic Pressure	10, 3	10, 3
Vibrating Wire Total Pressure Cell (VWTPC)	Total Pressure or Contact Pressure	5	5
Temperature sensors in the VWPZ, VWPZR, and VWTPC instruments	Temperature	10, 3, 5	2
Time Domain Reflectometers (TDR)	Volumetric water content	4	4
	Total =	100	36

The 1<sup>st</sup> phase of the ESP included monitoring until the end of 2013. In mid 2013, the data and sensor functionality were evaluated to determine whether or not the ESP should continue [12]. At that time, most of the sensors intended for long-term monitoring were still functional and providing data. The groundwater level was slowly rising on the 240 level where the large, irregular cross-sectional area made accurate estimation of groundwater inflow rate problematic. The vibrating wire sensors monitoring the groundwater level were not suitable to allow for accurate inflow extrapolation under low groundwater inflow conditions. Groundwater inflow rate is an important input for numerical modeling to assess long-term functionality and behavior of a shaft seal [11]. Having a low hydraulic conductivity, full-saturation of the clay component was recognized as being a long duration process. Consequently, continuation of ESP monitoring was required in order to obtain sufficient data to assess long-term performance of the shaft seal. Several challenges were faced in continuing the ESP monitoring beyond 2013. These challenges included reduced funding, complete demolition of the URL surface facility, and no electrical power at the

site after demolition. These conditions were not anticipated in the 1<sup>st</sup> phase of ESP (2009-2013).

In order to address these challenges, a new means to allow for continuation of ESP monitoring was developed. The ESP data in 2013 showed that the sensor readings were only changing gradually, so intermittent monitoring of the sensors would be sufficient to capture system evolution. Consequently, two portable readout boxes for vibrating wire sensors and fiber-optic sensors were selected for use in ongoing ESP monitoring. These systems do not require continuous electrical power and were proven to be accurate through comparison of the output of the automated monitoring system and manual readout boxes in the months prior to loss of facility infrastructure ([12], [13]). This 2<sup>nd</sup> phase of the ESP includes monitoring of the vibrating wire (VW) sensors (i.e., piezometers and total pressure cells), fiber-optic sensors (i.e., piezometers and total pressure cells) and TDR (Time Domain Reflectometer) sensors. The information associated with these sensors is provided in TABLE I.

Due to complete demolition of the URL surface facilities, the systems associated with long-term monitoring were relocated to a steel monitoring enclosure (2 m x 2 m x 2 m) placed near the top of the concrete shaft cap (Fig.2). The relocation was completed in April 2014, prior to demolition of the URL surface facility in order to minimize interference with the URL demolition process and to protect the leads associated with the sensors. The demolition of the last standing building at the URL site, the head frame, was done on November 17, 2014 (Fig. 2). The work was done without incident and did not affect the performance of the ESP monitoring sensors inside the monitoring enclosure. The ESP monitoring enclosure is now the only visible feature at the URL site. Fig. 2 shows its condition in November 2014 and October 2015. Permanent fences were installed around the enclosure in October 2015 as part of site safety requirements. When the ESP is eventually terminated (i.e., sometime after 2016), the steel monitoring enclosure will be removed from the site.

An initially unexpected lesson learned from the ESP was that extreme challenges such as the complete removal of infrastructure (e.g. buildings, electrical power, or internet connections) should be considered in the planning of post-closure monitoring RD&D or real life projects. In the ESP, these challenges were addressed by means of stand-alone manual monitoring systems. Some of the monitoring results obtained over the first 7 years of ESP monitoring are discussed below.

## **MONITORING RESULTS**

### **Temperature and Concrete Strain Monitoring**

Most of temperature changes observed in the concrete and clay components occurred within three months of concrete placement. They were the result of heat of hydration generated during concrete curing and its subsequent dissipation through adjacent

materials (rock and clay). The majority of the strains observed in the concrete were due to these temperature changes. After the concrete curing and cooling was essentially complete in March 2010, the temperature in and around the shaft seal stabilized at approximately 11-12°C where it has remained. Temperature evolution of the upper concrete component is illustrated in Fig.3. The 2<sup>nd</sup> phase of the ESP includes 2 selected temperature sensors to confirm temperature equilibration. Although the strain sensors were operational when monitoring was discontinued in 2014, no ongoing concrete strain monitoring is being done as part of 2<sup>nd</sup> phase of the ESP, because data collected up to 2014 indicated a system that was at equilibrium with no discernible ongoing strain [9].

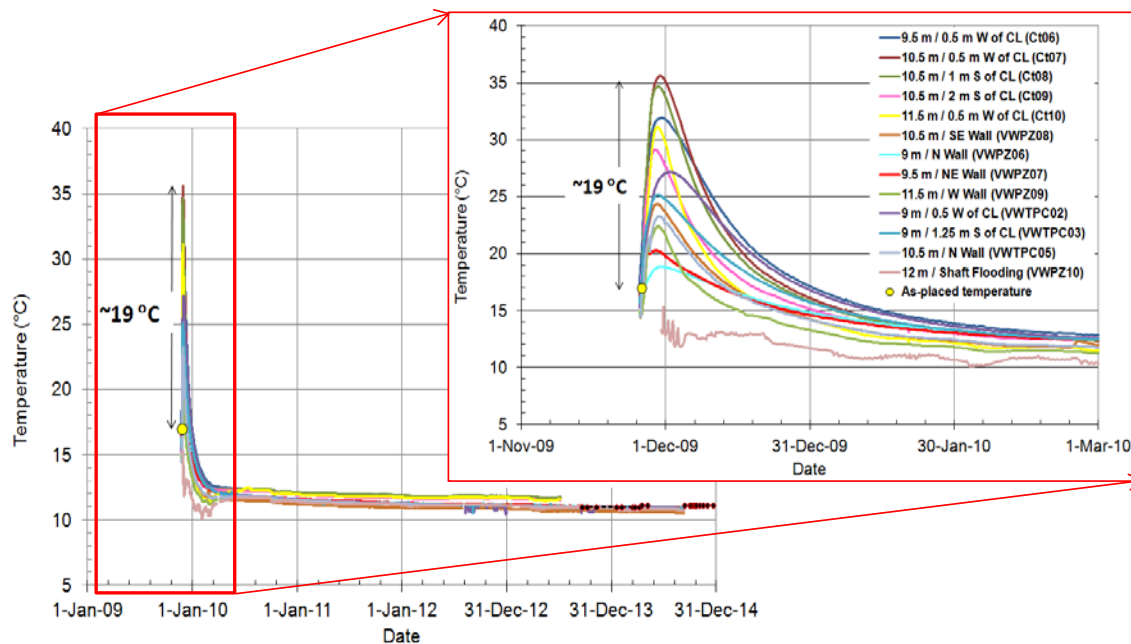


Fig.3. Temperature Evolution of the Upper Concrete Component

### Groundwater Level

A vibrating wire piezometer VWPZ10, installed at the top of the shaft seal is measuring the hydraulic pressure at the top of the seal, which allows the groundwater level to be calculated (Fig. 4). The important steps in system development are associated with changes in the slope of the hydraulic pressure-date graph in Fig. 4.

- In June 2010, the lower shafts were completely flooded and the flooding of the large volume of 240 Level begun.
- In July 2014, the 240 Level was completely flooded and water began to rise in upper shafts.
- As of June 2015, the water level had not reached the small horizontal excavations located at 130m depth (Fig. 4).

As of June 2015, the hydraulic pressure above the seal was approximately 740 kPa corresponding to a groundwater level of approximately 192.6 m depth, which was 41.6 m above the top of 240 level excavations (Fig. 4). At this level, the

cross-sectional area used to calculate the inflow rate is well defined and equal to the sum of the main shaft rectangular area (3.1 x 5.1 m<sup>2</sup>) and the vent raise circular area (i.e., a diameter of ~1.8 m). After seal installation, before the 240 level of the URL was closed in 2009, a higher inflow rate was estimated to be 4.3 m<sup>3</sup>/day [9]. Once the more uniform upper shafts began to fill in mid 2014, a better estimation of filling rate could be achieved and is currently estimated to be ~2.6 m<sup>3</sup>/ day. Fig. 4 also shows that there has apparently been a slight decrease in the inflow since January 2015. As the water level increases, the hydraulic gradient between current groundwater level to ambient groundwater level will decrease. The decrease of this hydraulic gradient results in the decrease of filling rate. The natural groundwater level at the URL prior to URL excavation in 1980 was located at a depth of approximately 20-25 m below the surface where the shaft is located.

It has been observed that the inflow rate changes over time and is determined by a complex interaction of subsurface water-bearing features as well as seasonally and climatically affected surface and near-surface processes. Assuming the currently observed inflow rate of 2.6 m<sup>3</sup>/day is relatively constant, the groundwater level will return to its ambient level in 2019. This is of course only an estimate, because the inflow rate will not be constant. Improving the understanding of the actual inflow rate is one of key goals of the 2<sup>nd</sup> phase of the ESP and will assist in understanding the performance of the shaft seal and regional groundwater evolution. These tools will be useful at other sites.

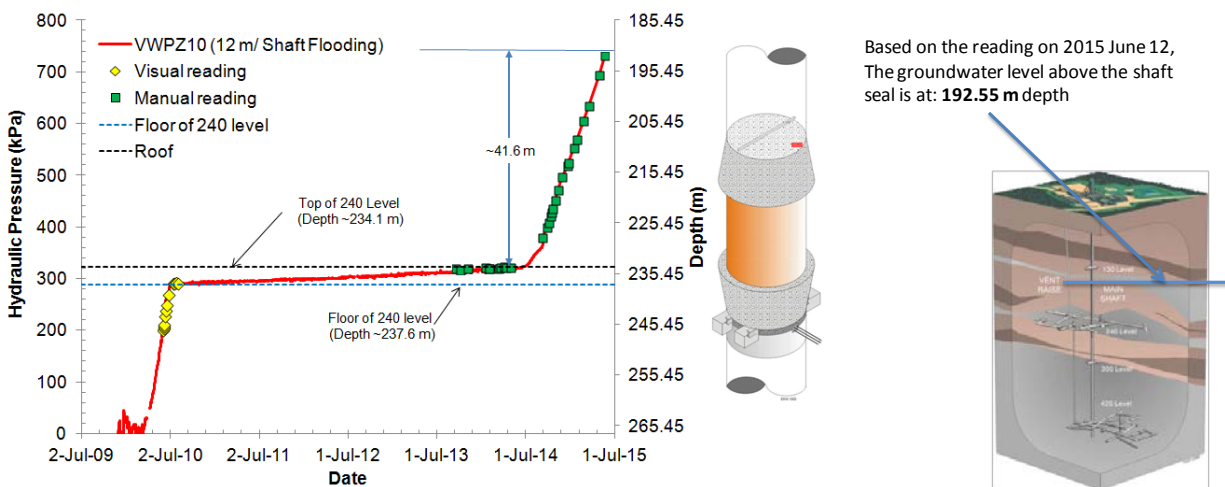


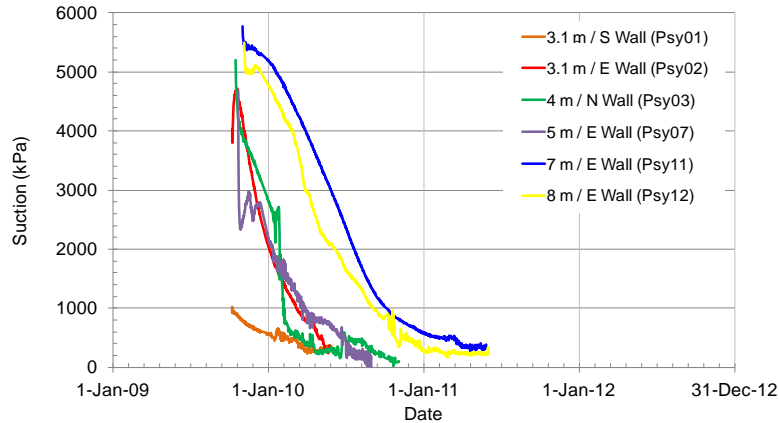
Fig. 4. Groundwater Level Above the Shaft Seal

### Water Uptake of Clay Component

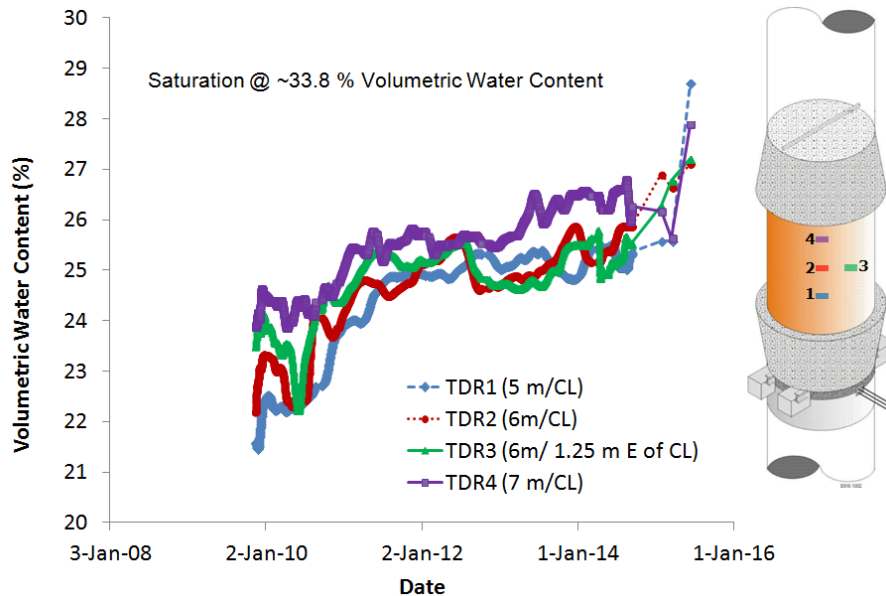
Water uptake in the clay component was measured using two different types of sensors: Vibrating Wire (VW) Psychrometers and Time Domain Reflectometer (TDR) sensors (Fig. 5). The water uptake at several locations near the perimeter of the clay components was measured using psychrometers (plots are provided in Fig. 5a). Due to the restriction on cable length from the sensors to the data logging system, the data logging system for the psychrometers was located underground at the 240 level. This data logging system was flooded and stopped working in July 2013, when the



groundwater level reached its elevation. This was anticipated during ESP design and as expected most of the psychrometers indicated saturation had been achieved by the time of logger failure.



(a) Suction in the clay component near shaft wall measured using Psychrometers



(b) TDR sensors

Fig. 5. Water Uptake Measurements

In addition to the psychrometers that were mostly located in the outer perimeter of the clay, four TDR sensors were installed to measure water uptake in the core of the clay component (Fig. 5b). These sensors have continued to be monitored and the core of the clay component has not reached full saturation yet. The maximum degree of saturation in that region was approximately 80% as of mid 2015 (Fig. 5b). Ongoing TDR monitoring was not initially planned to be part of the 2<sup>nd</sup> phase of the ESP. It was added in early September 2014 after investigation of the viability of doing intermittent readings was confirmed. Slow groundwater movement into the core regions of the

clay component is expected as the result of the very low hydraulic conductivity in the clay component. Continuation of TDR monitoring is therefore very important to developing an understanding of the behavior of the shaft seal in its unsaturated state.

A key aspect of the water uptake monitoring is the need to confirm that water uptake measurements from the TDR results are comparable to Psychrometer sensors. In the ESP, there were locations where these two different sensor types were installed close to each other in the clay component. These data can be used to calibrate the measurements from both sensors. As can be seen in Fig. 6, for the period where both sensors (Psy10 and TDR3) were operating, once their outputs were converted to saturation values, their outputs were comparable. This provides confidence that the readings from the TDRs can be used to estimate ongoing water uptake in the central portion of the clay component.

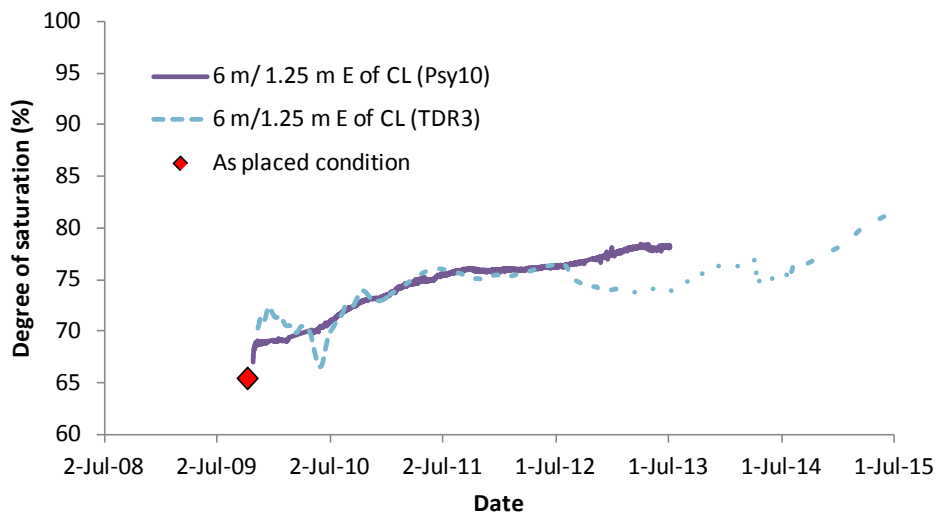


Fig. 6: Degree of Saturation from TDR and Psychrometer Sensor Located at the Same Location

Conversions of the suction measured by Psychrometer sensors (Fig. 5a) and volumetric water content measured by TDR sensors (Fig. 5b) to degree of saturation (Fig. 6) were required to compare the results of Psychrometer and TDR sensors, which are explained as follows. Assuming that the total volume of the clay component will be relatively constant, bulk density of clay will also be constant. Therefore common geotechnical volume-mass relationships (e.g., degree of saturation, gravimetric water content) can be calculated from volumetric water content. Conversion of the suction to degree of saturation required the soil water characteristic curve (SWCC) relationship of the clay component. SWCC defines the relationships of suction and degree of saturation and can be obtained from laboratory tests. Laboratory tests to determine SWCC were not performed for the ESP's clay component. Instead, the SWCC was estimated from available data on various bentonite-sand mixtures done in the past studies at CNL's former geotechnical laboratory and from literature reviews.

From this experience, if a large-scale experiment uses two different sensors to measure the same variable, it is recommended that two different sensors are installed at the same location to confirm their comparability. Additional laboratory tests of material components may also be required to analyze the results of large-scale tests.

### Total Pressures

Total pressure is being monitored at the clay-rock interface, clay-concrete interface, the contacts between concrete and rock, and within the clay component itself (Fig. 7). Based on swelling pressure data collected in laboratory studies of the same material as is installed in the ESP, it is anticipated that on achieving saturation and completion of shaft flooding, the swelling pressure component of total pressure will be in the order of 800 kPa and the pore water pressure component will be approximately 2600 kPa. This will result in a total pressure of approximately 3400 kPa that should be measured by the TPCs [7]. At present, under the existing hydraulic pressures, a saturated system should see total pressures of the order of 1600 to 1800 kPa at the lower concrete-clay interface. This has not yet been measured by any of the sensors in the ESP.

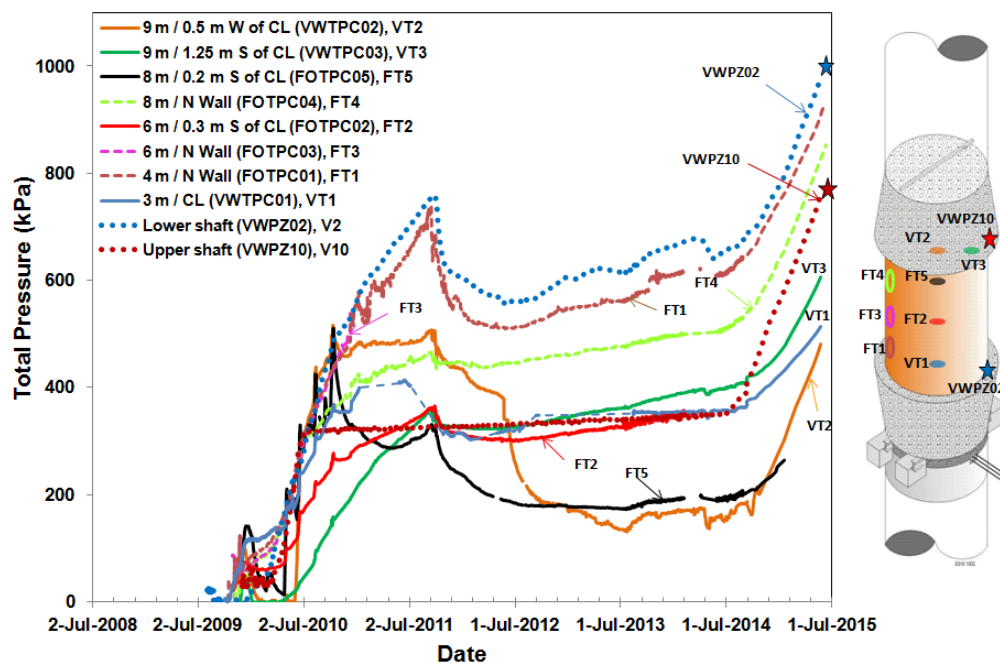


Fig. 7. Total Pressures in the Clay Component

Fig. 7 shows the total pressure cell (TPC) data collected in regions where the clay component is present, as well as the hydraulic pressures present at both upper and lower clay-concrete interfaces. It is clear from these data that the system is not in equilibrium and that water saturation of the entire clay component has not yet been achieved. This supports the conclusion that the clay component is not yet fully

saturated (TDR measurements (Fig. 6)). As the TPC sensors measure the sum of the swelling pressure, hydraulic pressure and mechanical load resulting from the mass of material overlying them, only slight differences in the output of these sensors should be evident once the system has fully flooded and equilibrated. The total and hydraulic pressure data collected between 2013 and 2015 continue to show a system that is gradually saturating, with the perimeter regions now likely saturated and as a result, restricting subsequent movement of water towards the as-yet unsaturated regions in the center of the clay-filled volume.

### Hydraulic Pressures

The hydraulic head differential across the seal is being measured using two VW piezometers located outside of the clay-filled region. Fig. 8 shows the hydraulic pressure measured in the region immediately below the clay portion of the seal and the free-standing water above the seal. The data for the piezometers used in this comparison are elevation-adjusted to the lower concrete-clay contact and the upper concrete-clay contact. Pressure difference between upper and lower concrete-clay contacts was calculated and is also shown in Fig. 8.

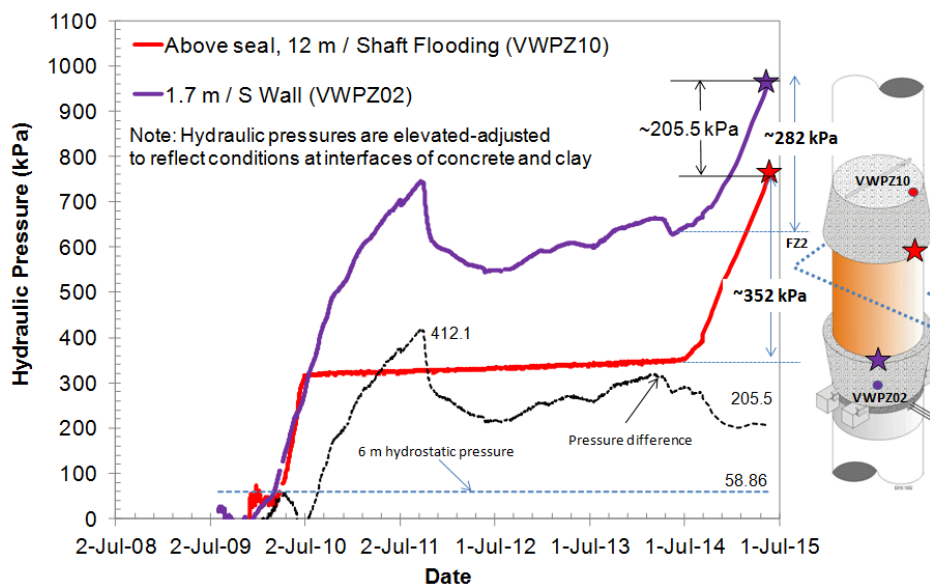


Fig. 8. Hydraulic Pressure Above and Below the Clay Component of the Seal

As of June 2015, a substantial pressure differential (~205.5 kPa, ~20.2 m) still exists across the 6-m-thick clay portion of the seal, which indicates the connection between the upper and lower shaft regions is restricted. At all times, this pressure difference was significantly greater than the hydrostatic pressure difference that would exist without the presence of the seal (~60 kPa). This indicates that the seal is providing effective resistance to water transport across it as any open connection(s) between the upper and lower shaft would result in loss of this pressure differential.

The results of the ESP are of relevance to repository closure planning and important to develop confidence in the functionality of shaft seals for nuclear waste repositories. Of

particular importance is the evaluation of the degree of isolation provided by the seal to the regions above and below its location. This may be indicated through the hydraulic pressure difference across the seal (Fig. 8).

## **PRELIMINARY NUMERICAL MODEL**

Preliminary hydro-mechanical (HM) finite element analysis was done using COMSOL Multiphysics to simulate the ESP's shaft seal saturation [11]. This model required evolution of groundwater elevation as one of the input parameters (Fig. 4). A 2D-axisymmetric geometry with simplified hydrogeological features was used. The model includes 2 different consecutive stages, illustrated in Fig. 9. Stage 1 simulates the changes of the groundwater pressure in an open shaft over 20 years. This stage simulates the changes of hydraulic pressure with time, focusing on the fracture zone area during the URL operation (Fig. 9a). Stage 2 simulates recovery of the groundwater pressure after seal installation. Due to the low hydraulic conductivity of the clay components and rock, recovery of groundwater pressure is a slow process. The numerical simulation covered up to 1000 years after seal installation. Limited comparisons with the ESP results were done in [11]. Development of improved numerical models is recommended in order to better understand the process occurring in the ESP.

## **CONCLUSIONS**

- Extreme conditions such as the complete removal of infrastructures (e.g. buildings, electrical power, or internet connections) should be considered in the planning of post-closure monitoring RD&D or real life projects. In the ESP, these challenges were addressed by means of stand-alone monitoring systems.
- The ESP continues to supply valuable information on the in situ evolution and performance of a full-scale shaft seal of the type that could be used in a nuclear waste repository. Information gained from monitoring the ESP can also be used to aid in the development of non-vertical (room and tunnel) seals in granitic or alternative geological media and to gain confidence in their performance.
- As of November 2015, the shaft seal at the URL is functioning as intended to limit the mixing of saline groundwater below Fracture Zone 2 (FZ2) and fresh groundwater above FZ2 and the majority of the ESP sensors intended to provide long-term monitoring continue to provide valuable data. The successful construction of the shaft seal and the demonstration of its functionality over time are both instrumental in building enhanced confidence in the long-term development and safety of a DGR.
- Full-scale monitoring, such as the ESP, combined with finite element numerical modeling are required to understand the long-term processes of multiple barrier systems to seal a DGR.
- Real life application of the knowledge gained from RD&D projects, such as the ESP, is likely not going to be needed for more than 100 years from the present time. Successful preservation of the knowledge related to both construction, monitoring and performance evaluation/modelling is very important to ensure that the ESP

results can be utilized by future generations when construction of repository seals are undertaken.

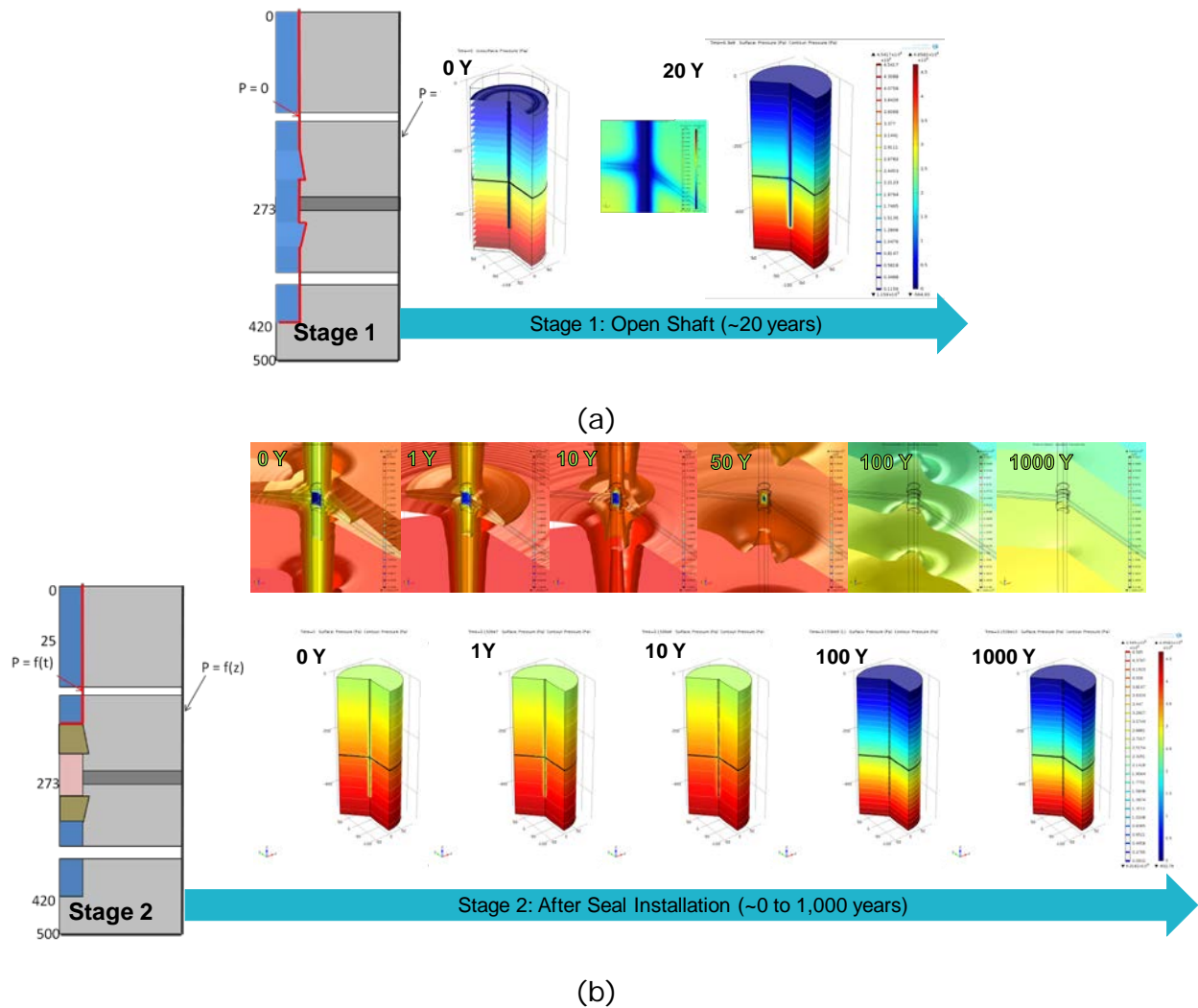


Fig. 9. Two Stages Hydraulic-Mechanical Models to Simulate the ESP [11]

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