Outcomes of the Full Scale Seal Experiment: A Seal Industrial Prototype for the Cigéo Project - 15207

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ASTRACT

The Full Scale Seal (FSS) Experiment is one of various experiments implemented by Andra, within the frame of the French HLW and IL-LLW Deep Geological Repository Project (aka Cigéo) development, to demonstrate the technical feasibility and check the performance of the seals which will be constructed in the shafts, ramps, drifts and disposal vaults, at time of Cigéo underground facilities progressive closure.

The FSS experimental objectives, principles and rationale were presented at WM'2013 (Paper 1306): FSS is a technological demonstrator built on surface, inside a concrete made horizontal drift model (also called the "test box"). FSS is part of the European DOPAS (Demonstration of Plugs and Seals) [2] project, under the umbrella of the Implementing Geological Disposal - Technology Platform (IGD-TP) [3] project.

FSS construction activities started in July 2012 and were completed in September 2014. The construction compliance assessment work activities are now ongoing (and will be continued until mid-2015).

This paper presents the construction and monitoring story of the FSS components, starting with the construction of a first containment wall based on a low pH self-compacting concrete (SCC), followed by the swelling clay core backfilling sequence and finishing with the erection of a second containment wall based on a low pH shotcrete.

The FSS experiment also enabled to qualify the commissioning methods applicable to an industrial sealing work at time of underground operations in the Repository. These commissioning methods are described and the results discussed. The equipment and methods used for the purpose of seal component construction and monitoring are presented. The physical characteristics obtained for each component of the seal are detailed and the compliance of measured values with the initial requirements is commented. The post-mortem work planned (e.g. coring and wire sawing of low pH concrete containment walls, use of penetrometer for the swelling clay core…) is also explained.

FSS is a first of a kind experiment, by its size, by the technical choices made. The first technical outcomes were presented to the French Nuclear Authority and to its Technical Support Organization. The successful implementation of the work carried out in the FSS drift model was positively assessed by the evaluators and deemed representative of the real underground conditions (industrial feasibility is proven).

This article concludes with a critical analysis of the methods and equipment used, of the results obtained and provides some perspectives of improvement for the construction of the first Cigéo industrial prototype seals scheduled around 2030 in ramps and horizontal drifts (provided the Cigéo construction is authorized in late 2020, and following the licensing request filing scheduled in late 2017).

INTRODUCTION

Andra's successful implementation of Cigéo relies on a sound demonstration of long term safety and on a relevant scientific and engineering basis as well as on social aspects such as stakeholders' acceptance and confidence.

The Repository progressive closure (by backfilling and sealing) policy is considered as instrumental in serving the above safety, technical and social objectives. The FSS experiment aims to raise the implementer's industrial know-how and the acceptance of the sealing strategy by the evaluators and the stakeholders, to whom FSS was presented during its implementation. The FSS experiment story and its outcomes are presented below.

The industrial stakes related to sealing activities are high, since, in the present Repository concept, there are up to 140 seals to be built in Cigéo during its progressive closure (Figure 1 shows the seal positioning principles as set up at this stage of design): it is particularly important to master the construction processes and the associated commissioning protocols and to evaluate the coactivity factor (i.e. the practical organizational relations between seal construction activities and nuclear operations).

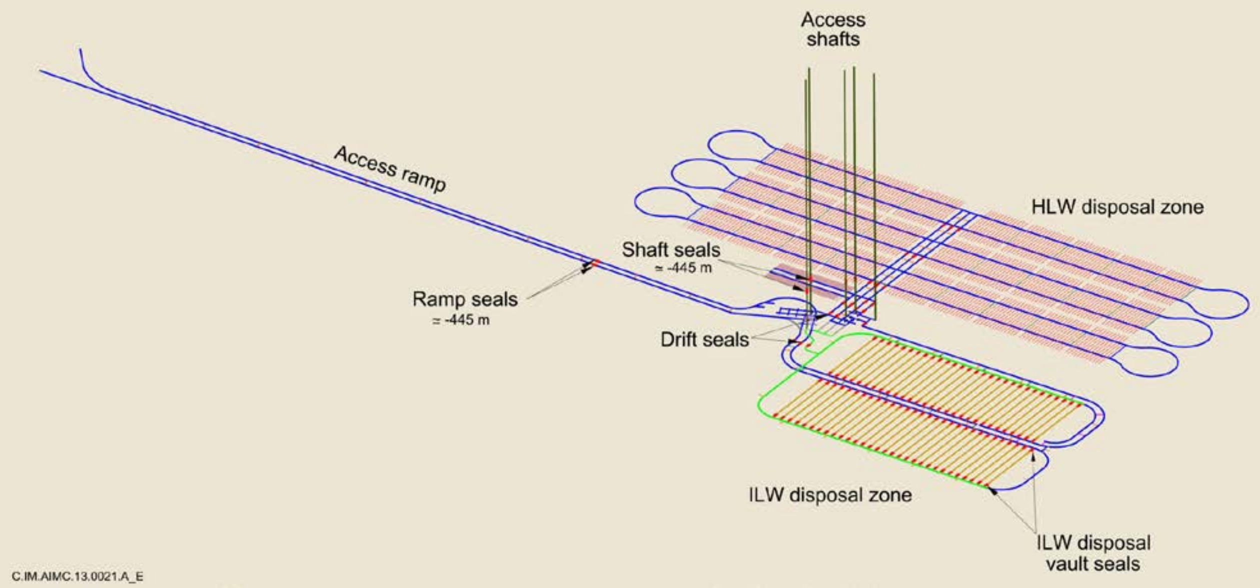

Fig. 1 - Positioning of seals (red dots) in Cigéo shafts, ramps, drifts and vaults

THE DOPAS PROJECT

The DOPAS project is a four year (2012-2016) cooperative project, financially supported by the European Community (EC) within the frame of the 7th Framework Program for Nuclear Research and Training (EURATOM). Its coordinator is POSIVA (Finland). It involves 8 countries and 13 partners coming from WMO (Waste management Organizations) in the EC and Switzerland, as well as from private companies or research institutes and universities with extensive experience in bentonitic and cementitious materials, modelling, instrumentations, and monitoring.

Andra's FSS is one of the 4 Full Scale Experiments carried out in DOPAS and is of concern for the Cigéo design part which relates to sealing activities in a clayish formation. The three other full scale plugging experiments are implemented in crystalline formations respectively by SKB (DOMPLU in Sweden), POSIVA (POPLU in Finland) and SURAO (EPSP in Czech Republic).

THE FSS RATIONALE

Drift Sealing Concepts in the French Deep Geological Repository

At time of Repository progressive closure, the sealing of shafts, ramps, horizontal drifts and disposal caverns must be assured by the construction of a specific barrier. The seal is composed of a swelling clay core (bentonite) with 2 low pH concrete containment plugs, one at each end. The remaining part of the underground openings is backfilled with the original excavated material (i.e. the argillites from the Callovo-Oxfordian formation constituting the host rock).

In the reference design, a horizontal seal is installed in a section of a horizontal drift/vault head, where the concrete liner will have been partly dismantled, thus allowing a direct contact between the argillite formation and the bentonite core, the swelling pressure of which should be close as close as possible to (but lower than) 7MPa (a value corresponding to the natural host formation stress). This conceptual design is illustrated in Figure 2.

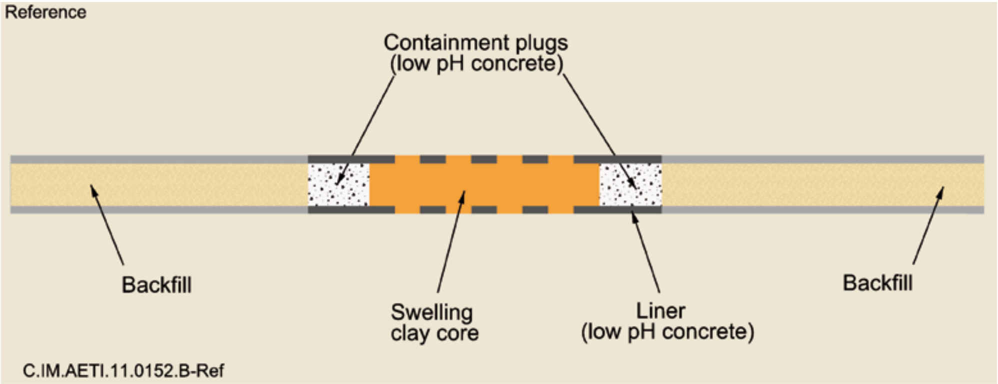

Fig. 2 - Reference horizontal drift sealing and backfilling concept.

The Various Seal Related Experiments and Tests Planned by ANDRA

In order to satisfy both the knowledge and demonstration needs in terms of phenomenology, safety assessment and engineering, a total of 4 main experiments have been planned by Andra in its demonstration strategy: three (3) scientific (phenomenological) experiments (ongoing, and including natural resaturation or forced/artificial hydration at various decimetric/metric scales or at scale ½ of Cigéo) and a technical one (FSS at scale 1/1 of Cigéo). All these experiments must be completed (or must provide significant data) before reaching the Cigéo license application filing milestone (end-2017).

The data availability is a challenge of its own, considering the time devoted to the resaturation of bentonite admixtures (up to several years at decimetric scale and up to several decades at metric scale). By combining the results obtained from the 3 phenomenological experiments and the FSS construction test, carried out at various scales and different experimental sites (on surface and in situ), and on various bentonitic materials (powder, pellets, bricks), Andra intends to cover all the aspects of the seal performance demonstration and provide some confidence to the safety evaluators. This approach was presented to them and deemed acceptable in July 2014.

Additional experiments and technological tests are forecast after 2017, including 2 Full Scale Demonstrators built in situ (in the Cigéo Pilot Zone) around 2030.

FSS CONSTRUCTION STORY

FSS Characteristics and specifications

FSS was built inside a concrete made drift model (also called the “test box”) fabricated for the purpose. The drift model was some 7.6m ID and 36m long. The drift concrete lining (70cm thick) and the formation break outs (recesses) likely to be generated by the drift lining deposition (up to 1m deep at the lining extrados) were simulated. Representative underground ambient conditions (temperature around 18-30°C, hygrometry between 50% and 75%) were maintained within the drift model, with a mine-type ventilation system installed at work front.

One low pH self-compacting concrete (SCC) containment wall and one low pH shotcrete containment wall, each 5m long and with a 250m^3 volume), closed the volume of the swelling core, on both sides. The bentonite swelling core (some 750m^3 of pellets/powder admixture) was some 14m long.

Figure 3 shows the concept of the FSS seal as constructed (at the end of the experiment) in its test box (the drift model) with the simulated recesses backfilled by bentonite or concrete.

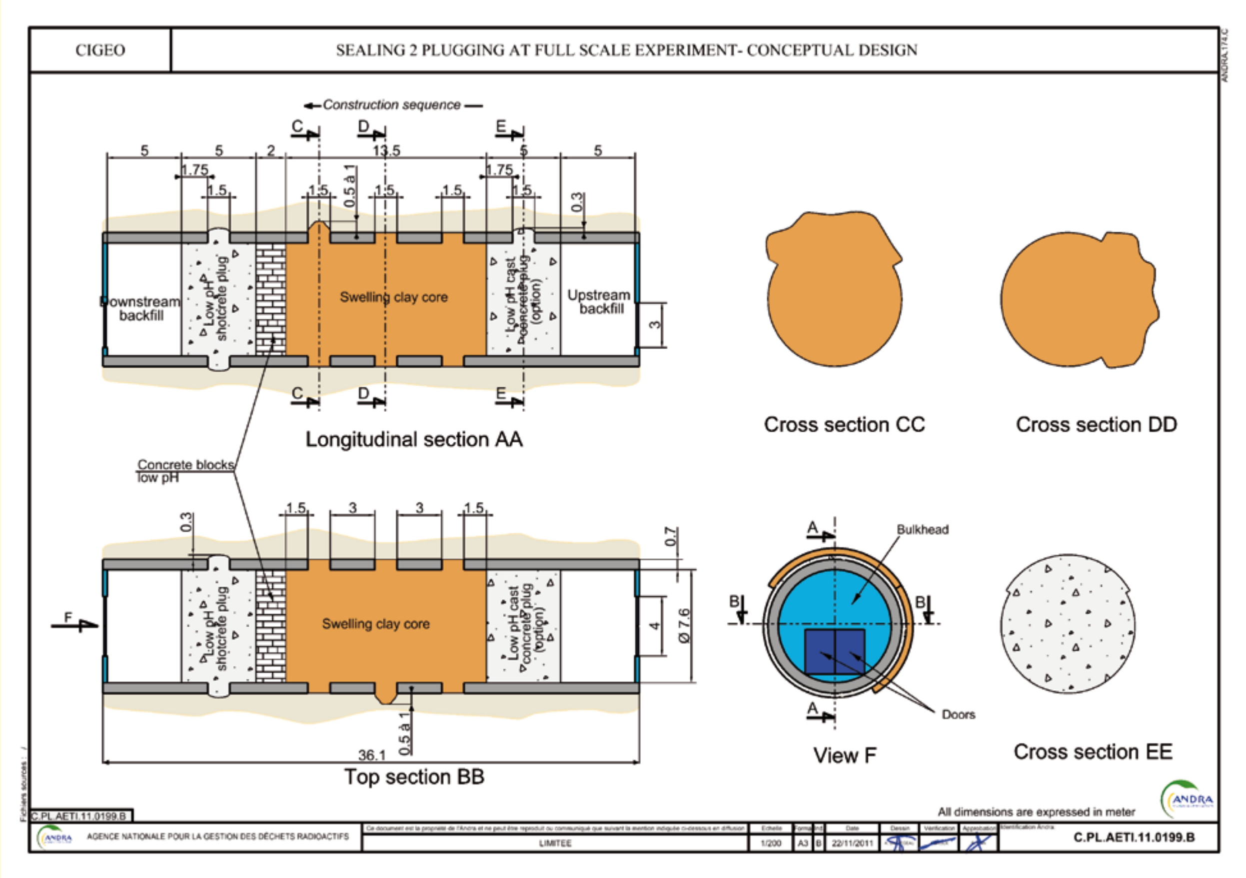

Fig. 3 - Longitudinal view of the FSS experiment as built in its test box.

The FSS experiment being a construction feasibility test, few quantitative specifications were issued; some were qualitative. They are indicated (without justifications) in the paragraphs specific of each seal component. For the same reasons, neither the bentonite material characterization phase nor the low pH SCC and shotcrete formulation development are described in this paper.

Construction of the test box (drift model)

The test box construction started on October 29th, 2012 and was completed in early June 2013. It was equipped (prior to its backfilling) with openings (observation windows) at its periphery and internally with temperature probes and shrinkage sensors for the low pH concrete containment walls and with TDR (Time Domain Reflectometry) sensors along the bentonite core emplacement zone. Figure 4 shows the FSS test box following its commissioning before the FSS backfilling start-up.

Fig. 4 - The FSS test box ready for seal construction

An information of interest was to measure as accurately as possible (by 3D scanning) the actual internal box volumes (for each section, and for each type of seal components concerned (swelling core or containment walls) to be filled in later. The information on the volumes measured was later cross-checked with the information on the volume of concrete and the mass of bentonite emplaced, as measured by operators at time of backfilling. This information enabled in particular to accurately assert the effective emplaced specific gravity of the pulverulent material constituting the swelling clay core.

Construction of the low pH SCC containment wall

The formulation of the low pH SCC took a few months and was validated at various volumetric scales (decimetric and metric in research labs, metric and decametric at the mixing plant and later at the test site), before proceeding with the pouring of the containment wall. The SCC composition is given in Table 1 below (pH value measured was less than 11 at 90 days).

Table 1: Composition of the concrete mixture for the low pH SCC containment wall construction

Components	**Quantity**
Rounded Gravel 5/12 (dry)	682.1 kg/m3
Sand 0/4 (dry)	698.7 kg/m3
Cement CEM III/A 52.5 L CE PM ES CP1 NF	130.0 kg/m3

Silica Fume	130.0 kg/m3
Filler	408.4 kg/m3
Glenium SKY 537 (Super Plasticizer)	*2.2%
Prelom 510 (Retardant)	*0.1%
Water	204.1 kg/m3

(*) Percentage of additives expressed as a ratio of binder (cement + silica fume + filler) weight

The FSS containment wall construction being scheduled in summer 2013, temperature was deemed to have a big impact on the SCC behavior at the fresh state. By reference to the concrete formulation pre-defined at the end of the testing and characterization phases, it was then decided to keep untouched the Superplasticizer (SP) dosage and to adjust the Retarding Agent (RA) content to the effective ambient temperature (especially during daytime, since at night the temperature was milder).

Moreover it was required that the maximal temperature reached during concrete curing and hardening should be less than 50°C. Thus, the heat emitted during hydration was assessed in lab and later used to estimate the maximal temperature at which the concrete could be poured on site to meet the requirement. In practice, it was decided not to pour concrete with an ambient site temperature greater than 26°C. Those ambient condition restrictions were effectively respected at time of casting operations.

The casting operations were preceded by preparation activities implemented in June 2013. The main issue was to design and erect a proper form:

- Similarly to what could be mounted underground in Cigéo, a one face form was used (by contrast with a traditional double form with cross bars),
- To withstand the pressure generated by the water-head appearing at time of pouring the semi-liquid concrete, a proper dimensioning of the form was carried-out and strengthening beams (bracons) were added at the rear of the form,
- To provide a leak-tight contact with the test box inner wall, it was decided to fix a support angle bar at the periphery of the box inner wall and to add a foam type flat seal between the face of the form and that of the angle bar,
- To prevent the rising of the “one face” form under buoyancy, an anchoring device was attached to the form thanks to a temporary concrete raft.

It was also necessary to install 4 washout vents: 2 pipes were set to release the air trapped when the concrete rises up into the test box recesses and the 2 others were pre-positioned for the future “containment wall to box liner” bonding operations.

The low pH SCC casting operations were carried out with 3 main objectives in mind: i) to realize a monolith type containment wall (~ 250 m3), ii) to abide by a maximum concrete curing temperature criterion of 50°C, iii) and try to limit as much as possible concrete shrinkage and cracking. For that purpose, it was decided to pour (mixing truck) batches of 7m3 each, with a stand-by time of 2 hours between two passes of pouring imposed, at the exception of the summital part (when one batch per hour was poured). The Figure 5 shows how the progressive casting of the containment wall was effectively carried out over time.

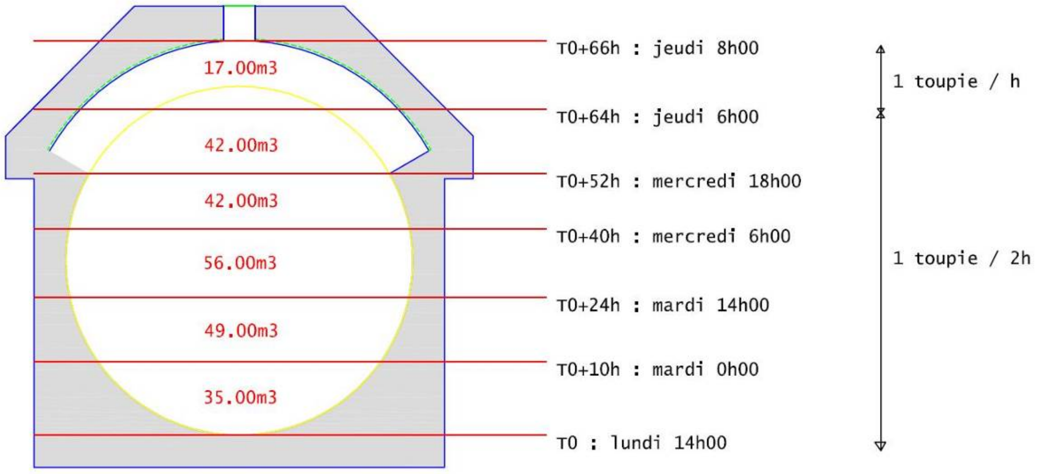

Fig. 5 - View of the low pH SCC containment wall concreting sequences

From a practical point of view, the fabrication of the low pH concrete batches took place in the concrete mixer plant located in Saint-Dizier (some 5 km from the FSS site), the same plant as that used for the preliminary concrete formulation and qualification phases. The concrete was transported by mixer trucks. Each mixer truck batch represented a layer about 15 to 20cm thick in the containment wall construction progress. The pouring speed was some 7m^3 in 20’ followed by 1h40’ in the waiting for the next mixer truck.

All the mixer truck 7m^3 batches passed a qualifying flow test before leaving the mixing plant and on site before proceeding with the pouring of the concrete. The spreading value was logged concurrently with the ambient temperature. The casting operations for which a concrete pumping truck was also mobilized went very well with the low pH concrete rising progressively inside the test box, with a smooth and regular emplacement (see Figure 6). To finish the operation, it was necessary to totally close the one face formwork and the concrete was injected in blind thanks to a concrete placing boom.

After its casting, the SCC containment plug was left for preliminary curing for about 1 week, and then the stripping of the form took place without difficulties. The temporary anchoring raft was also dismantled. Some 28 days of hardening later, the injection of a low pH slurry (grout) was started to bond the containment wall extrados with the test box concrete liner intrados. The quantity of injected slurry turned out to be very small (a few tens of liters). It was inferred that in this experimentation, there was little vacuum remaining or/and that the bonding had already taken place.

At the end of the casting and bonding operations, it was possible to watch a very homogeneous monolith without traces of cracks or fractures. The contact between the concrete monolith extrados and the box liner inner surface also looked excellent (see Figure 7).

Fig. 6 – Easy pouring and even emplacement of low pH SCC inside the test box

Fig. 7 - The low pH SCC containment wall as an end product

Construction of the swelling clay core

The swelling clay core backfilling sequence was also preceded by a metric scale emplacement test inside a sewage type concrete pipe (see Figure 8). This metric test helped to optimize the operating parameters: the rotating speed of the screw conveyors used to transport the bentonite powder/pellets admixture from the hoppers into the bentonite heap (progressively forming the core), the target value of the expected pulverulent material dry density (around 1.50), the natural slope of the heap (around 30%) and of course the bentonite admixture proportion: 30% of powder and 70% of pellets.

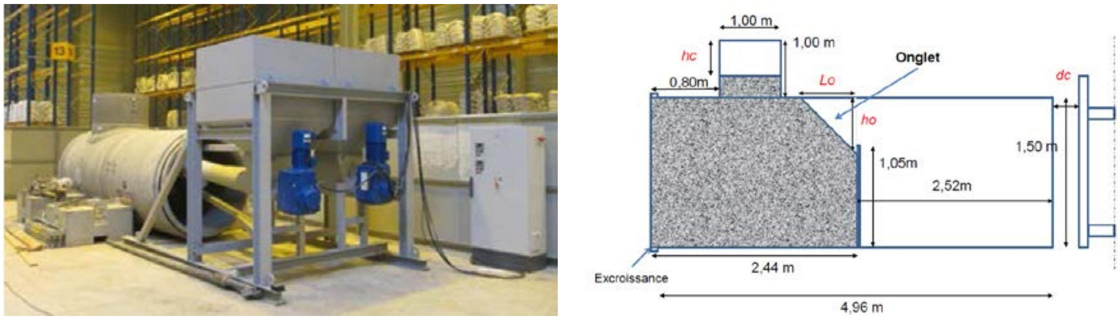

Fig. 8 - The metric test emplacement for bentonite admixture

The full scale swelling clay core backfilling sequence took place in 2 times (it was stopped at about mid-work because of a premature wear of the screw conveyors (the auger part), which led to a replacement of this piece of equipment). The backfilling sequence was then completed in summer 2014. At the end, the effective average density of the emplaced bentonitic material turned out to be quite close to that obtained during the preliminary metric test phase: 1.485 (vs. 1.50). The main issue was the density discontinuity / space variability of the emplaced material, due to the mechanical interference of the backfilling machine boom with the upper parts of the box: some of the recesses could not be filled in as well as expected. Figure 9 shows some of the backfilling activities and the size of the equipment mobilized for the purpose.

Fig. 9 - The swelling clay core emplacement operations

Construction of the low pH shotcrete containment wall

As for the SCC formulation, the development of the low pH shotcrete took a few months and was also validated at various volumetric scales (decimetric and metric scales in research labs, then on test panels both at the mixing plant and later at the test site), before proceeding with the construction of the second containment wall.

The shotcrete was easily sprayed in 10 to 15cm layers with a minimum time in the waiting (some 4 hours) between 2 applications. Rebound rate was minimized (some 10 to 12 % of total volume), but remained a concern for the quality of the construction: purging and cleaning (by the operators) of the rebound turned out to be a permanent “point of attention” for Andra’s supervisors. This second plug was completed on September 5th, 2014. Figure 10 shows the operator during shotcreting and the end result (a dome shape containment wall).

Fig. 10 - The low pH shotcrete containment wall construction (spraying/ left; end product/right)

FSS CONSTRUCTION COMPLIANCE ASSESSMENT ACTIVITIES

As mentioned ante some monitoring devices were preliminarily installed in the test box to evaluate:

- The concrete shrinkage and temperature evolution with time,
- The bentonitic material backfilling quality (mainly in the recesses).

The Figure 11 shows where the various sensors and probes were positioned for later assessment of the construction work. At this stage of evaluation the main outcomes are:

- For the SCC monolith: an excellent shrinkage value (less than 300 µm/m) and a curing temperature which never exceeded 45°C (targets were less than 350 µm/m and 50°C respectively);
- For the shotcrete monolith, some deviation is noticed: temperature rose up to 67°C (above target, but less than 70°C which is deemed critical). Shrinkage value is not available yet (not stabilized);
- For the swelling clay core, the TDR sensors show a relatively poor presence of bentonite in the upper parts of the recesses.

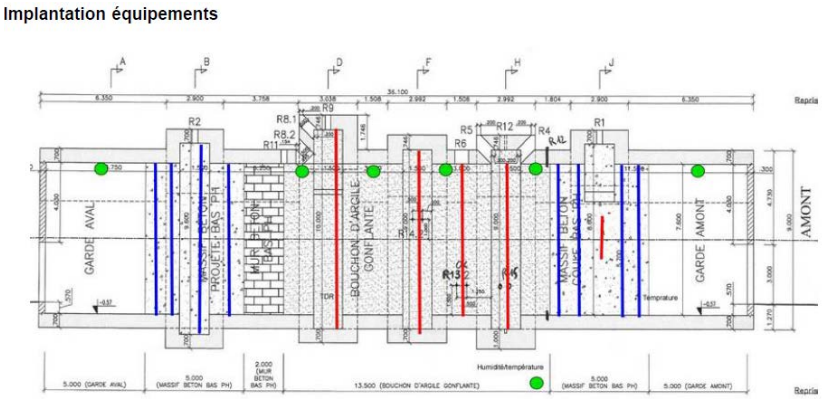

Fig. 11 – Monitoring sensors as pre-positioned in the test box before seal construction

Some additional investigations are now on the way:

- For the swelling clay core, some gamma-gamma logging was carried out, evidencing a good radial and longitudinal homogeneity of the bentonitic material (at the exception of the upper parts of the recesses). This will be completed and confirmed by penetrometer tests planned in the early 2015.
- For the low pH monoliths, various cores have been taken and the samples are undergoing analysis: pH values (should be equal or less than 10.5 after 1 year of curing and hardening), porosity, compressive strength. The next step is the wire sawing (scheduled in mid-2015) of the 2 containment walls, which will provide a unique opportunity to check the homogeneity and cohesiveness of the construction at large, as well as the quality of the low pH concrete bonding with that of the OPC concrete forming the test box lining.

CONCLUSION

The FSS construction test has proven the industrial constructability of the horizontal seal components, as designed in Cigéo. Of course, there is room for various improvements in the processes and significantly better results can be obtained. The main improvements identified to date are listed:

- Containment wall concreting operations: as much as possible, the use of low pH SCC should be preferred to that of low pH shotcrete, even if the preparatory work (positioning of forms) takes some time. The quality of the SCC obtained is far better than with shotcrete. Furthermore, once the form is installed, the productivity (by pumping) is very good and well adapted to the volumes expected in the Repository. Finally, the mixing (preparation) of the SCC is easier than the shotcrete one, which also requires a permanent supervision (to take care of the rebound) during spraying operations. It is also considered not to go for a secondary bonding with slurry, since the “concrete to concrete” contact looks excellent (to be confirmed after wire sawing).
- Swelling clay core backfilling operations: the dust appearing during the transfer of the bentonite powder (from big bags into the backfilling machine, and then into the heap forming the core) must be dealt with seriously to improve the worker’s health and safety conditions (increasing the mine type ventilation will be needed, partitioning of the sealing zone from the nuclear zone will also be mandatory to prevent potential HEPA filter clogging). Concerning the residual summital voids (in the upper recesses), an additional backfilling device must be added (e.g. preliminary spraying of shotclay) in order to reach a more homogeneous and higher density of the emplaced bentonitic material).
- Some additional commissioning devices could be developed (e.g. real time measurement of bentonite material emplaced versus volume backfilled).

These improvements (and other not identified at this stage) should be incorporated in the “full scale demonstrators” which are required by the Nuclear Safety Authority in the early stage of Cigéo (during the Pilot Phase), around 2030: one seal in a horizontal seal (in a real drift) and another one in a ramp. Their successful achievement will be a requisite to proceed with further operations in the underground nuclear facility.

REFERENCES

1. http://www.andra.fr/
2. http://www.posiva.fi/dopas/
3. http://www.igdtp.eu/

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