DOPAS Work Package 4 Deliverable 4.1
FSS Experiment – Report on Qualification of Commissioning Methods

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The report has been reviewed internally by Andra for approval.

The DOPAS coordinator (Johanna Hansen for POSIVA) has also reviewed the report and approved it for submission and uploading on the EC data base.

APPROVED FOR SUBMISSION:

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Executive Summary

Report Background

The Full-Scale Demonstration of Plugs and Seals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). The DOPAS Project is running 48 months (September 2012 – August 2016). Fourteen European WMOs and research and consultancy institutions from eight European countries are participating in the DOPAS Project, coordinated by Posiva (Finland). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of DOPAS.

The DOPAS Project aims to improve the industrial feasibility of full-scale plugs and seals, the measurement of their characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. It is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination and is led by Posiva. WP2, WP3, WP4 and WP5 address, respectively, the design basis, construction, compliance testing, and performance assessment modelling of five full-scale experiments and laboratory tests. WP2, WP3, WP4 and WP5 are led by SKB (Sweden), Andra (France), RWM (United Kingdom), and GRS (Germany), respectively. WP6 and WP7 address cross-cutting activities common to the whole project through review and integration of results, and their dissemination to other interested organisations in Europe and beyond. WP6 and WP7 are led by Posiva.

The DOPAS Project focuses on drift, vault, tunnel and shaft plugs and seals for clay, crystalline and salt rocks:

- Clay rocks: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a surface facility at St Dizier, is an experiment of the construction of a drift and intermediate level waste (ILW) disposal vault seal.
- Crystalline rocks: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research centre (URC) and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland.
- Salt rocks: tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts-ELSA) experiment, being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by laboratory testing performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Each experiment represents a different stage of development:

- The Swedish experiment was started prior to the start of the DOPAS Project and was pressurised during the early stages of the Project.
- The Finnish, Czech and French experiments were designed and constructed during the Project. Initial pressurisation of the Finnish and Czech experiments occurred within the last year of the Project.
- The French experiment was not pressurised, and dismantling of the experiment was undertaken during the Project. The pressurization is in fact carried out in a separate experiment called REM, also described in WP4 DOPAS Deliverable 4.2 "Report on Saturation Test" Conil *et al.*
- The German tests focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

This present report "FSS Experiment Report on Qualification of Commissioning Methods" is Deliverable D4.1 of the DOPAS Project, and is part of WP4.

This Deliverable addresses the issues of commissioning and investigations methods as they have been implemented in the full-scale experiment FSS (during its construction and later during its dismantling) within the course of the DOPAS Project, and more precisely:

- What did the investigations and monitoring devices used during the FSS construction (and post mortem "clever dismantling") bring in terms of knowledge about the state of compliance of the seal components "as built"?
- Were the investigations and monitoring devices used (to evaluate the compliance and performance of FSS components) appropriate and sufficient (qualitatively and/or quantitatively) or did they show some limitations? Are they "qualified"?
- Are they transposable (fit for industrial use) to seal components commissioning methods in Cigéo, be it for the construction of the full scale seal demonstrators as envisaged during the Pilot Phase (2025/2034) or later (in decades) for the final repository closure operations, i.e. at end of waste disposal operations?

Note 1: In this document, there is no description of "qualification procedures" (in the acceptation of QA) of the monitoring/investigation tools, systems and means deployed in FSS. There is rather a series of statements of expert opinion like "is this given tool or system "qualified" or "adapted" for the commissioning job in the future"?

Note 2: Consideration is also given to the need for "a better calibration" of the tools used in FSS for investigation purposes.

The main properties investigated and common to Cigéo seal components and the FSS experiment design specifications (cf. WP2 DOPAS Deliverable D2.1 "Design Basis and Criteria Report" White *et al.*) are summarized below:

- Concrete strength (Compressive resistance) at 28d-90d.
- pH value of concrete leachate at 28d-90d.
- Curing temperature of concrete (hardening period and later).
- Concrete shrinkage and cracking.
- Average (global) and localized density of dry emplaced bentonite.

The FSS experiment design and construction outcomes are otherwise described in more details in Deliverable D3.1 "FSS Experiment Construction Summary Report" Bosgiraud *et al*. which belongs to WP3 of DOPAS, while Deliverable D4.8 "FSS Experiment Summary Report" Bosgiraud *et al.* provides an overlook of FSS global performance.

Evaluation of the Commissioning Methods carried out in FSS

The FSS experiment is a test aimed at demonstrating the technical feasibility of constructing a drift and intermediate level waste (ILW) vault seal at full scale. The drift model (aka "test box") has an internal diameter of 7.6 m and is 35.5-m long. FSS includes a swelling clay core supported on each side by a low-pH concrete containment wall.

Andra tested two types of low-pH cementitious materials for the containment walls: upstream, it was low-pH self-compacting concrete (SCC) and downstream low-pH shotcrete. Andra designed, produced and used a bentonitic mix made of pellets and powder to backfill the core volume.

The FSS experiment is focused on the construction of the seal components. The performance (good functioning) of the monitoring equipment (positioned inside the test box) before construction works and the nature of investigations which followed the bentonitic material/concrete emplacement operations are described in the present report D4.1 and consideration is given on their applicability to Cigéo.

1. Investigation and Monitoring of the 2 Concrete Monoliths

The monitoring system (**temperature and shrinkage sensors**) installed inside the SCC/shotcrete containment walls was able to reliably monitor the curing temperature and shrinkage of the two types of low pH concrete:

- The curing temperature and shrinkage in the self-compacting concrete (SCC) containment wall was less than what was specified (i.e. were compliant with requirements);
- Conversely, requirements were not fully met for the shotcrete wall.

These sensors look fit for future use in Cigéo, even if their installation is intrusive: their wiring implies passing through the concrete monoliths, but this is of no structural/mechanical impact on the containment walls, while the potential hydraulic by-pass thus created is of no consequence, since the abutments have no hydraulic function in the reference seal concept.

Investigation of the concrete monoliths was carried out by wire sawing, photography, and sonic survey and coring.

- Wire sawing cannot be repeated on a Cigéo monolith which must preserve its mechanical functions, but photography (mapping of the monolith visible face) is a good and relatively straightforward way to look at the concrete homogeneity, to evaluate the quality of contact between 2 cast/sprayed layers or between the monolith concrete and liner concrete walls (same for the contact grouting). Mapping of cracks (width, extension) can also be carried out, as well as sonic survey, to investigate the cracks depth if doubt arises about the cracks size and penetration. These operations are however time consuming and do not provide enough information on the concrete quality deep inside the wall. Additional investigation systems may have to be explored if the structural integrity of the monolith is at stake (e.g. in case shrinkage or temperature values, as measured by the monitoring system, are not compliant with the performance requirements specified).
- Coring (combined or not with sawing) of the concrete monoliths was used as an efficient mean of investigation during post-mortem dismantling of FSS. This method cannot be generalized to routine operations in Cigéo. One may however decide to core a seal monolith in Cigéo, but up to a certain extent and according to a certain pattern (this action will have to be debated with (and agreed by) the nuclear authority or its TSO), if doubt arises about the monolith compliance (see example above about non-compliance of concrete temperature or shrinkage values);
- A good cross checking between the mass balance (hence the volume) of the concrete poured (sprayed) and the volume to be backfilled will help to evaluate if any significant void are left unfilled. The same can be done for contact grouting operations.

2. Investigation and Monitoring of the Bentonite Core

The **time domain reflectometer** (**TDR sensors**) device installed inside the test box provided qualitative information on the space density variation and homogeneity of the bentonite backfilling, in particular for the core summital recesses. As anticipated, residual voids appeared and segregation of the bentonite admixture occurred. This TDR system still needs further calibration for a quantitative use. It could be considered in the construction of the future full scale seal demonstrators planned in the Cigéo Pilot phase. However, TDR technology will most likely not be incorporated in the making of the real Cigéo seals, since its installation inside the swelling clay core is intrusive (unless reliable and lasting wireless methods are developed by that time).

The **gamma-gamma** logging tool, run through pre-installed pipes positioned inside the swelling clay core volume, has qualitatively confirmed the presence of residual voids and evidenced segregation of the bentonite admixture in the summital recesses of the core. This technology also needs additional calibration work to become a quantitative measurement tool. Besides, this logging tool must be run inside pre-installed pipes only, which is by nature an intrusive solution. At this stage, this TDR monitoring system is not considered fit for use in Cigéo, but its opportunity of use may be re-envisaged for the full scale demonstrators planned during the Cigéo pilot phase (i.e. 2025-2034).

The **penetrometer** tool deployed by Andra before dismantling FSS was the most satisfactory system tested so far to quantitatively evaluate the space variability of dry emplaced density of the bentonitic mix backfilled in the drift model. It provided quantitative data. Even if the calibration has to be improved and is specific of a given bentonitic mix, this technology is deemed as the most promising and most handy device for commissioning the swelling clay core at the end of the core construction.

The **mass balance approach** used to evaluate the average dry emplaced density of the swelling clay core consisted in confronting the initial/residual volumes to be backfilled with the bentonitic mix vs the cumulated mass of pulverulent material already emplaced. This approach turned out to be effective and straightforward. The main improvement identified is the need for a more efficient (faster) 3D scanning system, providing “on time” data on the residual volumes to be backfilled.

3. Data acquisition system (DAS)

The Local DAS (Data Acquisition System) by GeoMonitor was installed at vicinity of the test box, to register the values measured by sensors (concrete hardening temperature and shrinkage values, TDR data).

It was also used for the collection of other operations linked parameters, such as the topographical evolution of test box during filling operations, the registering of videos taken during operations, and finally the ambient air relative humidity and air temperature values.

This DAS system worked very well, no flaws noticed. It was connected via an FTP site with Andra’s Central Data Acquisition System (by SolData), for redundancy in acquisition.

This approach, already implemented by Andra for monitoring various scientific experiments in the Bure URL infrastructures, turns out to be quite effective. A similar system and redundancy approach are considered for future Cigéo seal construction operations.

Conclusions

The FSS experiment has demonstrated that it is feasible to industrially build a horizontal seal system in the Callovo-Oxfordian host rock considered for the French Cigéo repository. This demonstration has included verification of compliance of the seal components as built, thanks to the monitoring systems and investigation methods deployed for commissioning purposes.

The list of acceptance criteria (those which will be declined in quantitative parameters with contractual tolerances for commissioning the seal components) has still to be formalized.

Concerning the monitoring and investigation tools potentially deployed for commissioning, one must say that for most of them, there is still a need for additional development (e.g. calibration) or specific adaptation to the objects built, before a “qualification” is granted to the commissioning tools concerned.

These further developments and the qualification steps will have to be scheduled well ahead of underground operations, when planning the future Cigéo closure activities and first of all before the construction of full scale seal demonstrators as envisaged during the Cigéo pilot phase (i.e. 2025-2034).

List of DOPAS Project Partners

The partners in the DOPAS Project are listed below. In the remainder of this report each partner is referred to as indicated:

Posiva	Posiva Oy	Finland
Andra	Agence nationale pour la gestion des déchets radioactifs	France
DBETEC	DBE TECHNOLOGY GmbH	Germany
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	Germany
Nagra	Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Switzerland
RWM	Radioactive Waste Management Limited	UK
SÚRAO	Správa Úložišť Radioaktivních Odpadu (Radioactive Waste Repository Authority – RAWRA)	Czech Republic
SKB	Svensk Kärnbränslehantering AB	Sweden
CTU	Czech Technical University	Czech Republic
NRG	Nuclear Research and Consultancy Group	Netherlands
GSL	Galson Sciences Limited	UK
BTECH	B+ Tech Oy	Finland
VTT	Teknologian Tutkimuskeskus VTT Oy (VTT Technical Research Centre of Finland Ltd)	Finland
UJV	Ustav Jaderneho Vyzkumu (Nuclear Research Institute)	Czech Republic

List of Acronyms

AECL:	Atomic Energy of Canada Limited
ASN:	Autorité de Sûreté Nucléaire (Nuclear Safety Authority in France)
BMU:	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Germany)
BMWi:	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy in Germany)
Cigéo:	Centre Industriel de Stockage Géologique (Industrial Repository in France)
DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation damaged zone
EE:	Expert Elicitation
ELSA:	Entwicklung von Schachtverschlusskonzepten (Development of shaft closure concepts)
EPSP:	Experimental Pressure and Sealing Plug
FSS:	Full-scale Seal
GBT:	Green Break Technology
GPR:	Ground penetrating radar
HRL:	Hard Rock Laboratory
ILW:	Intermediate-level waste
LASA:	**La**ngzeitsicherer **S**chachtverschluß im S**a**linar (long-term safe shaft closure in salt)
LAVA:	**La**ngzeitsicherer Schacht**v**erschluß im S**a**linar (long-term safe shaft closure in salt)
LECA®:	Light-weight expanded clay/concrete aggregate
LVDT:	Linear variable differential transformer
OPC:	Ordinary Portland Concrete
PHM:	Physical Hydraulic Model
PIM:	Physical Interaction Model
POPLU:	Posiva Plug

PVDF:	Polyvinylidene fluoride
R&D:	Research and development
RSC:	Rock Suitability Classification
SCC:	Self-compacting concrete
STUK:	The Finnish Nuclear Regulatory Authority
TC-Tests:	Triaxial compressions tests
TDR:	Time domain reflectometer
THM-Ton:	Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (investigation of THM processes in the near field of a repository in clay)
URC:	Underground Research Centre
URCF:	Underground Rock Characterisation Facility
URL:	Underground research laboratory
WMO:	Waste management organisation
WP:	Work package

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1 Introduction

1.1 Background

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- The German tests focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

This present report “FSS Experiment Report on Qualification of Commissioning Methods” is Deliverable D4.1 of the DOPAS Project, and is part of WP4.

1.2 Objectives

The objectives of this report D4.1 are to provide an integrated state-of-the-art summary of the outcomes of FSS, concerning the issues of monitoring means and investigation methods as they have been implemented in the full-scale experiment FSS (during its construction and later during its dismantling):

- What did the investigations and monitoring devices used during the FSS construction (and post mortem “clever dismantling”) bring in terms of knowledge about the state of compliance of the seal components “as built”?
- Were the investigations and monitoring devices used (to evaluate the compliance and performance of FSS components) appropriate and sufficient (qualitatively and quantitatively) or did they show some limitations?
- Are they transposable to seal components commissioning operations in Cigéo, be it for the construction of the full scale seal demonstrators as envisaged during the Pilot Phase (2025/2034) or later for the final repository closure activities, i.e. at the end of the waste disposal operations?
- What outstanding technical and operational issues remain and what modifications are necessary to achieve routine technical use of the tools and devices considered for monitoring and investigation?

Note: there is no discussion of the "Qualification methodology" per se (in the acceptation of Q/A) of the tools, systems and methods described in this report. There is rather a series of statements of opinion like "is this given tool or system "qualified" or "adapted" for the commissioning job"?

The main properties investigated and common to the FSS experiment design specifications (cf. WP2 DOPAS Deliverable D2.1 "Design Basis and Criteria Report" White *et al.*) are summarized below:

- Concrete strength.
- pH of concrete leachate.
- Curing temperature of concrete.
- Concrete shrinkage and cracking.
- Average (global) and localized density/swelling pressure of dry emplaced bentonite.

The FSS experiment design and construction outcomes are described in Deliverable D3.1 "FSS Experiment Construction Summary Report" Bosgiraud *et al*. which belongs to WP3 of DOPAS, while Deliverable D4.8 "FSS Experiment Summary Report" Bosgiraud *et al*. provides an overlook of FSS global performance.

1.3 Scope of D4.1 Report

Link to other main DOPAS and FSS related Deliverables

This report (D4.1) is part of a series of WP2, WP3 and WP4 FSS related or DOPAS related Summary Reports describing the outcomes of the technical work carried-out in the FSS experiment. The reports were produced partly sequentially and partly in parallel, but represent an integrated suite of documents describing the FSS outcomes from the perspective of each WP. As such, there are cross-references between each report, which reflect the position at the end of this experiment, when all of the FSS related reports, in all the WPs, are complete and published.

The other FSS concerned reports are:

- DOPAS Work Package 2, Deliverable D2.1 "Design Bases and Criteria", White *et al*. (2014).), which describes the design basis for the FSS experiment as considered in the DOPAS Project.
- D3.1, "FSS Construction Summary Report" (Bosgiraud *et al.*, 2016) summarises the work undertaken and the lessons learned from the detailed design and construction of the FSS experiment. These include the full-scale demonstrator construction, the preliminary laboratory work and its progressive upscaling, and the learning provided by the practical experience in implementing the experiment.
- D3.30, "WP3 Final Summary Report: Summary of, and Lessons Learned from, Design and Construction of the DOPAS Experiments", White *et al.* (2016) summarises the work undertaken and the lessons learned from the detailed design and

construction of all the full scale experiments undertaken by the DOPAS partners during the course of the Project.

- D4.4, the WP4 "Integrated Report" (White *et al.*, 2016) summarises what has been learnt with respect to the repository reference designs for plugs and seals for all of the experiments undertaken in DOPAS. D4.4 also considers the feedback from the work which may include modifications to the design basis.

Freeze Dates for Experiment Information in this Report D4.1

This report is based on progress reached up to the following dates (timeline):

- For FSS, design work was undertaken in the period August 2012-April 2014, the upstream low pH SCC containment wall was cast in July 2013, the swelling clay core was emplaced in August 2014 and the downstream low pH shotcrete wall was emplaced in September 2014.
- Investigations of FSS were undertaken in the period October 2014 to July 2015, while dismantling and rehabilitation of the surface facility was completed in December 2015.

1.4 Terminology

Throughout this report consistent terminology has been applied. The key terms are listed:

- The term used to describe the combination of materials in a specific concrete is *mix*. In specific cases, this term replaces the use of *formulation* and *recipe*.
- The term used to describe a test of a seal component at a reduced scale is *mock-up*.
- In this FSS related report, and by difference with other reports produced by other DOPAS Project participants, a seal is composed of 3 main components: a central swelling clay core maintained by a concrete containment wall (abutment) on each side.

For the FSS experiment, the consideration of *performance* of the seal components is dealt with in WP5 Reports of DOPAS, which is concerned with modelling of the post-closure evolution of plugs and seals (post-closure performance assessment), consideration of the representation of plugs and seals in total system safety assessment. The WP4 Deliverable D4.2 "Report on bentonite saturation test" Conil *et al.*, also covers a metric-scale experiment (REM) undertaken in support of FSS.

Hence, the reader must keep in mind that the *performance* of the seal components is about their compliance with pre-defined specifications, while the *performance* of monitoring systems / investigation tools is about their good functioning and their appropriateness for a future routine commissioning job in Cigéo.

2 Andra’s Drift and ILW Vault Seal and related FSS seal design

This chapter summarizes the FSS experiment as tested within the DOPAS Project, in particular the design, construction and dismantling phases of the FSS experiment, with respect to Andra’s reference drift and ILW vault seal:

Note: The FSS experiment does not address the long-term behaviour of Andra’s reference drift and ILW vault seal. Long-term behaviour is addressed in complementary experiments, including the REM experiment, which is described in the DOPAS Work Package 4, Deliverable D4.2 “Report on Bentonite Saturation Test (REM)”, Conil *et al.* (2015).and referenced therein. As a consequence monitoring issues related to REM are not dealt with in the present report D4.1.

2.1 Design Basis for Andra’s Drift and ILW Vault Seal

Drift and ILW Vault Seal Safety Functions

In France, high-level waste (HLW) and ILW will be disposed of in a repository referred to as the “Centre Industriel de Stockage Géologique” (also known as Cigéo). The repository is located at a depth of some 500m, in a clay host rock (argillite) in the Meuse and Haute Marne Departments of Eastern France. The primary function of the repository is to isolate the waste from activities at the surface and its second function is to confine radioactive substances and control the transfer pathways which may, in the long term, bring radionuclides into contact with humans and the environment (Andra, 2013). The principal contribution of the seals in Andra’s concept is the containment of radionuclides.

In Andra’s concept, seals are defined as hydraulic components for closure of large-diameter (up to 10m) underground installations and infrastructure components. The safety functions of the drift and ILW vault seals are specified in the following qualitative sense:

- To limit water flow between the underground installation and overlying formations through the access shafts/ramps.
- To limit the groundwater velocity within the repository.

Drift and ILW Vault Seal Design

There are 3types of seals envisaged in Andra’s disposal concept: shaft seals, ramp seals, and drift and ILW disposal vault seals. Each seal consists of a swelling clay core and 2 concrete containment walls (cf. Figure 2.1).

The swelling clay core provides the required long-term performance of the seal, whereas the containment walls are included to mechanically contain the clay core (especially following saturation when the bentonite will swell and exert pressure on the walls and host rock).

The primary difference between the different types of seal (shaft, ramp, and drift and ILW vault) is the extent to which the concrete lining of the tunnels is removed before installation of the swelling clay core. Shaft and ramp seals will be located in the upper part of the

Callovo-Oxfordian Clay host rock, which is more competent than the lower part as it contains more carbonates and, therefore, will generate less damage of the rock during construction and pose less risk to workers from falling rocks. As a consequence, complete removal of the lining prior to installation of the swelling clay core can be considered as a reference for shaft and ramp seals; this ensures a good contact between the clay core and the rock, and so a better hydraulic performance. For the drift and ILW disposal vault seals, which are located in the lower parts of the host rock where it has a higher clay content, only partial removal of the lining is envisaged.

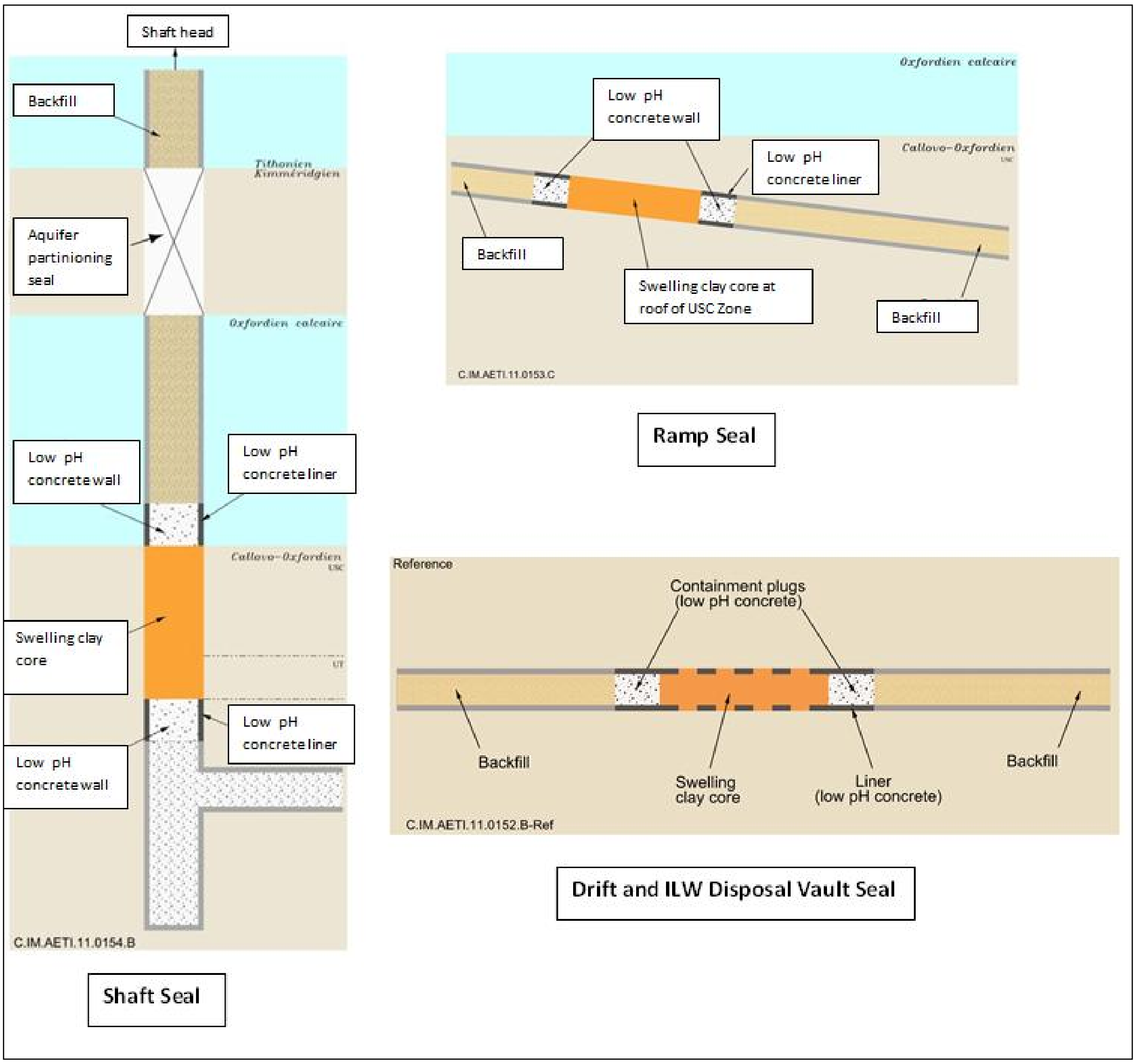

Figure 2.1: Schematic illustration of the conceptual designs for shaft, ramp, and drift and ILW disposal vault seals for the Cigéo reference disposal concept (Andra).

Key Design Specifications in the FSS Design Basis

The key design specifications contained within the design basis and which are directly tested through measurement and monitoring the FSS experiment or during materials development are presented in Table 2.1. More information on the design basis can be found in DOPAS Work Package 2, Deliverable D2.1 "Design Bases and Criteria", White *et al.* (2014).

The FSS full design basis contains a much greater number of requirements; only the most significant design specifications have been listed here and are considered in this report.

Table 2.1: Key design specifications tested through measurement of the results of the FSS experiment or during materials development as part of the experiment (measures provided by monitoring or in situ investigation are highlighted in **green)**.

ID	Design Specification	Justification	Compliance Approach
FSSDS01	The pH of concrete shall not exceed a value of 11, and shall ideally lie between 10.5 and 11 at 28d.	At pH < 11, the impact of cement leachate on bentonite and argillite performance is acceptable.	Three recipes tested in the laboratory (B50 CEM III/A; B50 CEM I; and B40 CEM III/A).
FSSDS02	The maximum curing temperature of SCC and shotcrete of containment walls shall not exceed 50ºC.	Ettringite can form in concrete at temperatures above 70°C and lead to expansion and cracking, and a consequent loss of strength in the concrete. Maximum curing temperature is set to avoid the possibility of this process occurring, and takes into account the ambient temperature of the Cigéo repository (i.e. ~20 ºC).	Measurement of peak curing temperature in SCC and shotcrete containment walls.
FSSDS03	Strain as a result of shrinkage of concrete shall be less than 350µm/m at 90 d.	This design specification is linked to a design requirement which states "*The heat of hydration shall not cause the temperature to generate heterogeneities in the mechanical behaviour of concrete or shotcrete, in particular causing localised cracking.*" The concrete walls need to confine the swelling clay Temperature gradients result in cracking that would reduce the strength of the concrete walls and create an interface resulting in larger than expected displacements of the concrete walls. Therefore, the requirement has been defined in terms of strain. A 350µm/m value has been specified by reference to more traditional values (500µm/m) that are commonly found in civil engineering.	Monitoring of strain (shrinkage) in the concrete walls.

ID	Design Specification	Justification	Compliance Approach
FSSDS04	Cracking of the concrete shall be minimised to be as small as possible.	Cracking would reduce the strength of the concrete walls. Cracking could also lead to flow through the concrete walls, which may lead to bentonite erosion and, consequently, a reduction in density of the clay.	Observations during dismantling to confirm no through-going cracks have formed in the concrete monolith.
FSSDS05	The low-pH SCC shall have a characteristic compressive strength of at least 30 MPa at 28 d and 40 MPa at 90 d.	The values are for standard concrete strength, and they are consistent with parameters used in Andra's models.	During the materials development phase, the low-pH SCC was tested in the laboratory. In addition, tests were undertaken of the low-pH SCC containment wall constructed at full-scale. These tests included measurement of surface hardness and sonic velocity in order to demonstrate the quality of the emplaced concrete consistent with existing standards.
FSSDS06	The low-pH shotcrete shall have a characteristic compressive strength of at least 25 MPa at 28 days and 35 MPa at 90 d.	The values are for standard concrete strength, and they are consistent with parameters used in Andra's models.	During the materials development phase, the low-pH SCC was tested in the laboratory. In addition, tests were undertaken of the low-pH SCC containment wall constructed at full-scale. These tests included measurement of surface hardness and sonic velocity in order to demonstrate the quality of the emplaced concrete consistent with existing standards.

ID	Design Specification	Justification	Compliance Approach
FSSDS07	The dry density of the bentonite materials used in the swelling clay core shall be 1,62 kg/m^3.	This design specification is linked to a design requirement which states "*The swelling clay materials, pure or with additives, shall ensure that an overall swelling pressure of 7 MPa is reached on the whole core, and a maximum hydraulic conductivity of 1 x 10^{-11} m/s throughout the core.*" An effective mechanical stress of 7 MPa is required to counter-balance the host rock natural mechanical stress (less than natural stress can result in reactivation of EDZ, higher than natural stress results in more fractures). The effective mechanical stress is a result of an *in situ* stress of 12 MPa balanced by 5 MPa pore pressure (hydraulic head), resulting in 7 MPa. During material testing, the dry density value of 1.62 kg/m^3, corresponding to a swelling pressure of 7 MPa after hydration, was specified to ensure that the required swelling pressure could be achieved. Performance assessment studies conducted prior to the DOPAS Project showed that the seal performance can meet the prescribed safety functions (see Section 4.1.1) with a hydraulic conductivity of 1 x 10^{-9} m/s. However, 1 x 10^{-11} m/s was specified for the FSS experiment because it was considered by Andra to be an achievable value. The density required to achieve a hydraulic conductivity of 1 x 10^{-11} m/s is significantly lower than the density required to achieve a swelling pressure of 7 MPa, and, therefore, the density value was predicated on the swelling pressure requirement only. Further details on the design work that led to the dry density specification are provided in White *et al*. (2016).	Compliance with the density requirement was determined through mass balance of the bentonite materials used in FSS, time domain reflectometer (TDR) penetrometer measurements and gamma-gamma logging.

2.2 Summary of FSS Experiment

Objectives of FSS

The main objective of the FSS experiment is to develop confidence in, and to demonstrate, the technical feasibility of constructing a full-scale drift and ILW disposal vault seal. The experiment is housed in a concrete "test box" at a surface facility. The test box is a model (scale 1:1) of a repository drift in which the ambient conditions (air temperature, humidity and ventilation) are controlled (and monitored) such that they are representative of the Cigéo underground environment.

Technical feasibility includes demonstrating the ability of the approach used to emplace the clay core to be suitable for filling recesses in the clay host rock, i.e., any potential breakouts generated during the removal of the concrete support lining. Therefore, the concrete test box includes recesses that mimic breakouts. The conceptual design of the FSS experiment is illustrated in Figure 2.2.

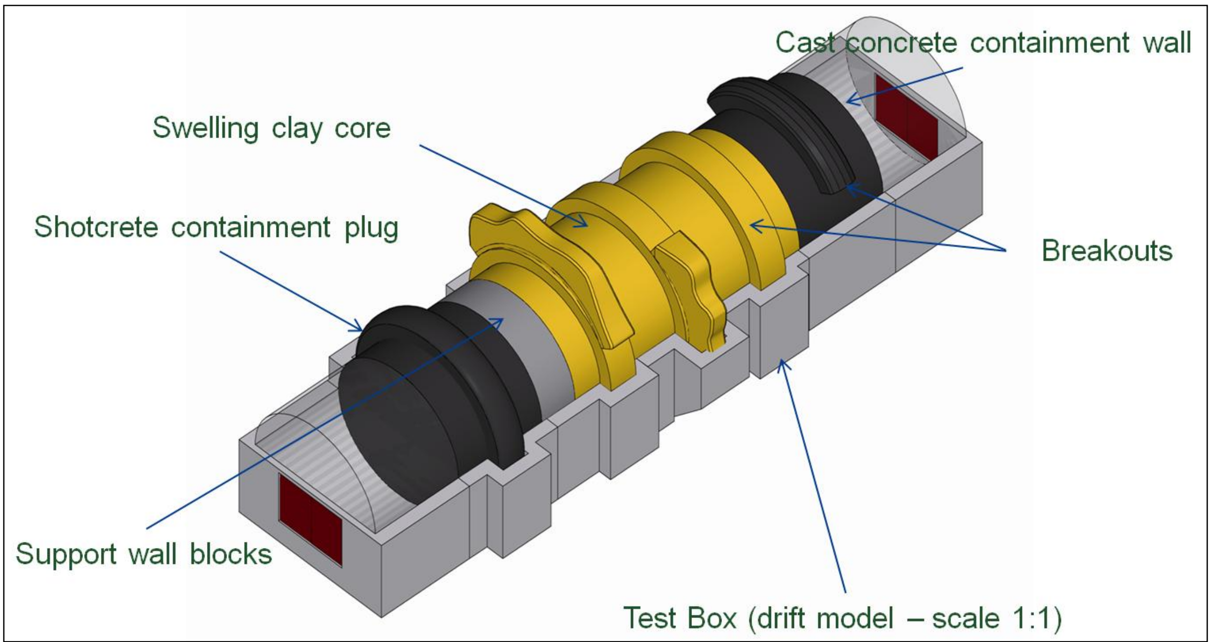

Figure 2.2: Schematic illustration of the FSS experiment design.

The main geometrical difference between the Cigéo reference seal design and the FSS experiment design for the Andra drift and ILW vault seal is the length of the seal. The real seal underground will be longer than the seal considered in FSS. The FSS experiment investigates two types of low-pH containment wall, one using self-compacting concrete (SCC) and the other using shotcrete, to allow the preferred method to be selected and incorporated later into the reference concept. Further information on the FSS experiment conceptual design and design basis is presented in DOPAS Work Package 2, Deliverable D2.4 "WP2 Final Report: Design Basis for DOPAS Plugs and Seals", White *et al.* (2016).

As the experiment is focused on the construction and installation of the seal, the materials will not be saturated or otherwise pressurised. Complementary experiments are being undertaken in parallel with FSS. These include the REM experiment (WP4 Deliverable D4.1, Conil *et al.*, 2015), which consists of an “as close as possible to *in-situ* conditions” resaturation test undertaken in a surface laboratory with the same pellets/powder mixture as that used in FSS, at a metric scale (the REM experiment is planned to last some decades).

Not pressurised, the FSS experiment has been dismantled within the period of the DOPAS Project. This activity is referred to as “clever” dismantling by Andra. The term “clever” is used by Andra to describe the dismantling of the FSS experiment as the activities incorporate additional observations and the collection of additional information related to the properties of the installed components. By collecting further information during dismantling, Andra benefits from a more thorough assessment of the works carried-out, at a marginal additional cost and at a marginal extra-delay.

Summary of FSS Design and Construction

The design and construction of FSS included the following activities:

- Materials development and testing to select the concrete mix for the low-pH SCC containment wall, the concrete mix for the low-pH shotcrete containment wall, and the bentonite materials for the low-pH swelling clay core.
- Siting and construction of the FSS test box.
- Installation of the seal components.
- Monitoring and investigations.
- Dismantling combined with additional investigations.

A summary of these activities is provided below. Further details are provided in the WP3 D3.30 Summary report (White *et al.*, 2016), as well as in WP3 Deliverable D3.1 (Bosgiraud *et al.*) and referenced therein.

Learning Related to Operational Issues

The lessons learned from construction of FSS and the implications for installing seals in Cigéo are summarised as follows:

- For the low-pH SCC, it was found that the temperature at the experiment site impacts on concrete, therefore, this will need to be appropriately managed underground. It was decided not to pour concrete when the ambient temperature was greater than 26°C (see D3.1 for background). The ambient temperature in the Cigéo repository at the time of containment wall emplacement will similarly impact the curing temperature, and hence the performance of the concrete. Although this situation is not expected to arise in Cigéo, mitigation measures, such as the use of cooled water for the concrete mix or the positioning of cooling pipes inside the containment wall, could be implemented if this situation would arise (it is anticipated that heat dissipation in the host rock will probably be less efficient than inside and through the FSS test box).

- During clay core emplacement, one of the main challenges was dealing with the dust generated by handling of bentonite in the warehouse. This was the main health hazard issue in FSS. Bentonite materials transfer and handling systems will have to be optimised to minimise the dust generated (e.g., by using a conveyor system and dust covers), while specific (additional) ventilation will have to be installed. Other ventilation/dust suppression methods could also be incorporated alongside the filling processes (e.g., water mist). In practice, the main operational safety issue is not linked to the seal construction *per se*, but to the preparatory work, when partial dismantling of the drift liner will have to be carried out and followed by purging of the host formation (to get rid of flakes at the contact with the formation wall) and local (temporary) reinforcement of the rock (at roof) by bolts and mesh.
- The use of shotcrete in a mine-like environment can be very useful in building maintaining structures (drift walls in particular: in this application the maximum layer of shotcrete does not exceed a thickness of some 15 to 20cm). In the case of low pH concrete containment walls, where the cumulative thickness of layers is several metres, the heterogeneity of low pH shotcrete and the cleaning/purging of rebounds is a challenging issue. In addition, the mechanical characteristics of shotcrete are significantly heterogeneous by comparison with those of a low pH SCC. It is, therefore, recommended to limit the use of low pH shotcrete to less significant components when building a containment wall (e.g., surfacing the concrete bricks forming the support wall) and during the construction of the vault/drift wall (e.g., shotcrete might be used for building the initial temporary drift wall support while SCC is for the final drift liner).

2.3 Performance of FSS Components based on Measurement and Monitoring during Installation

In this section the performance at the time of installation of the FSS experiment with respect to the design specifications listed in Table 2**.1** is evaluated:

- The performance of the SCC and shotcrete containment walls with respect to the curing temperature (FSSDS02) and strain (FSSDS03) design specifications is commented;
- The performance of the bentonite swelling clay core with respect to the bentonite density design specification (FSSDS07) is discussed.
- The systems used to measure and monitor the installation of the FSS components are described hereafter and are illustrated in Figure 2.3, Figure 2.4 and Figure 2.5.

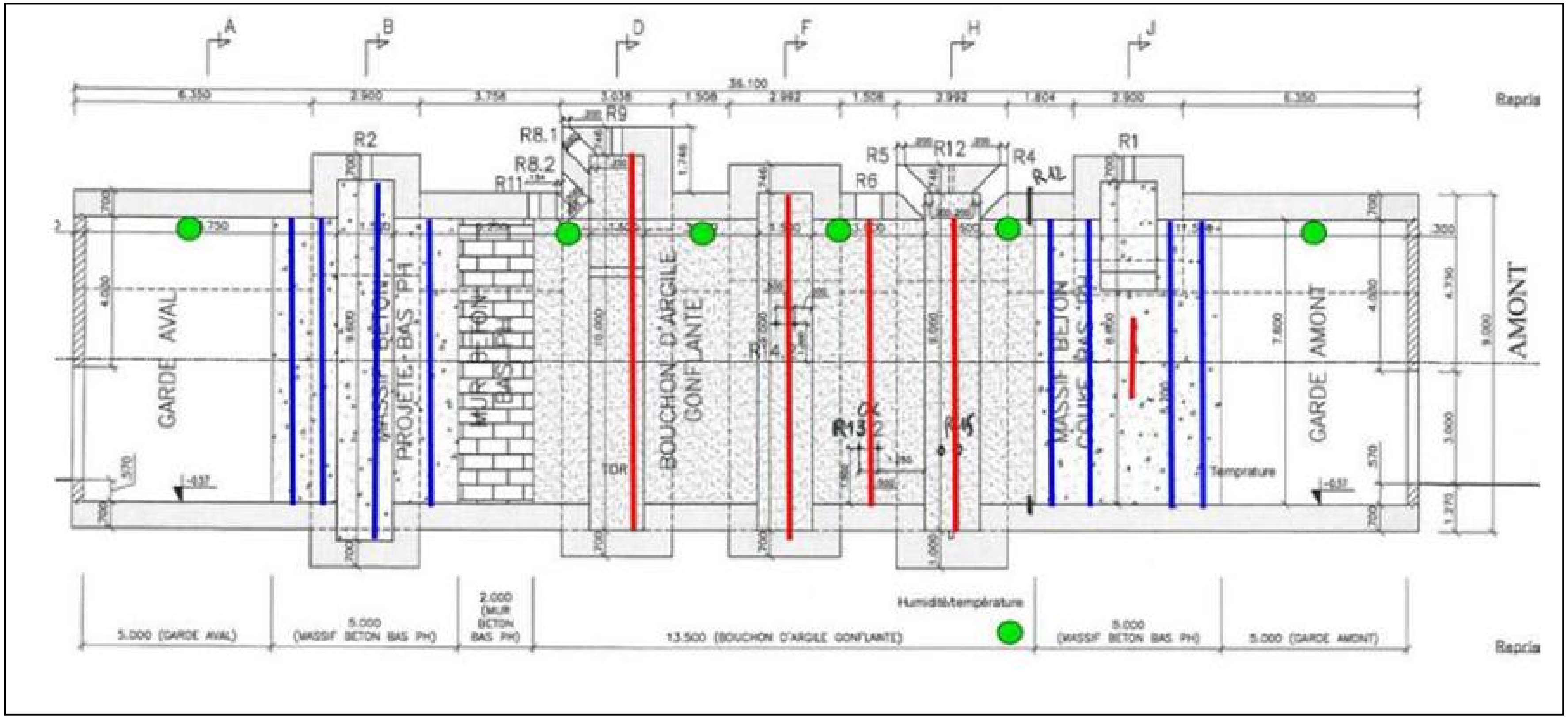

Figure 2.3: Location of the different sensors in FSS (**blue**: strain and temperature sensors in the low-pH concrete containment walls; **green**: relative humidity and temperature sensors; **red**: TDR sensors located in the swelling clay core).

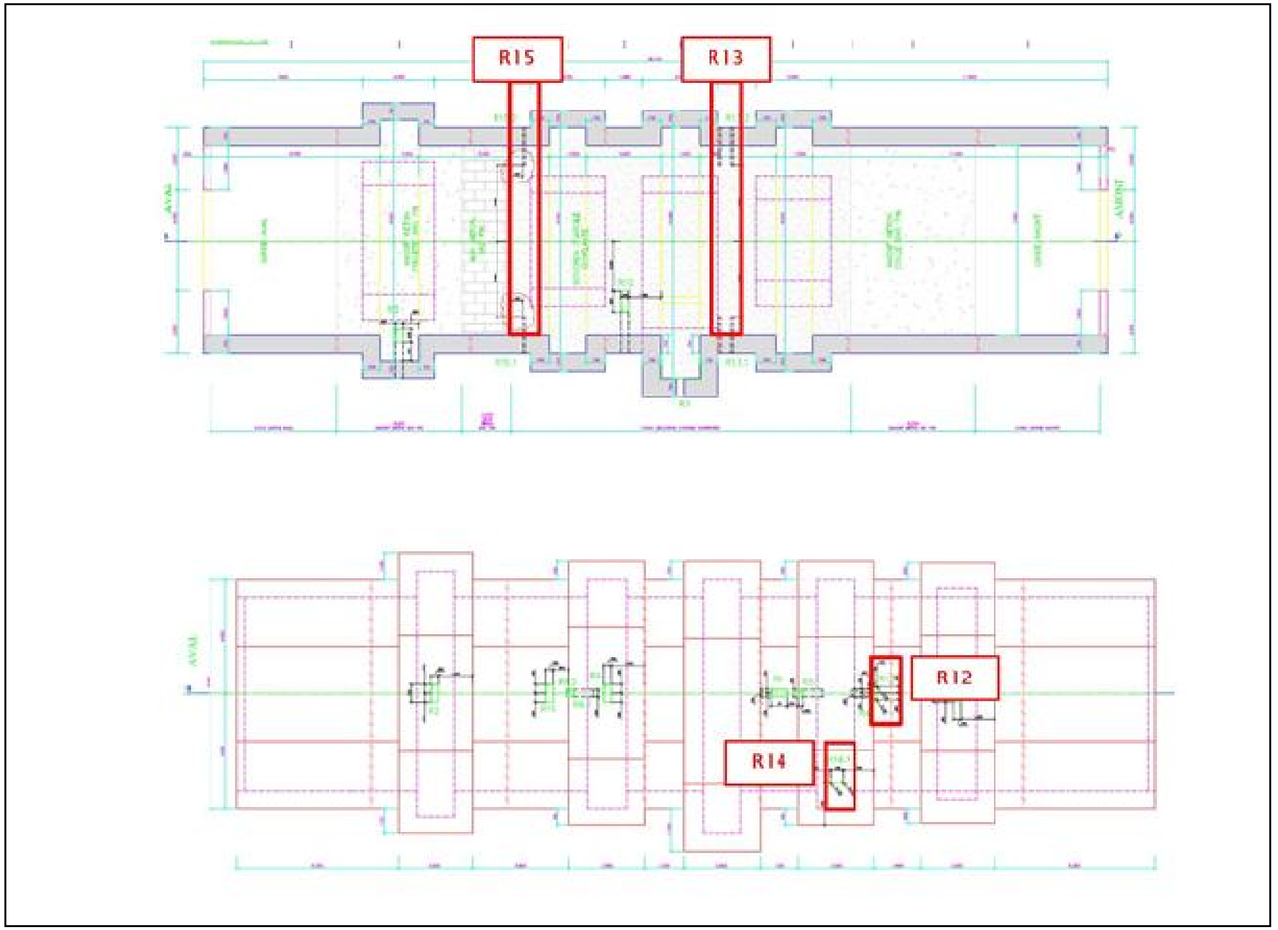

Figure 2.4: Location (**in red**) of the different pipes pre-positioned in FSS for gamma-gamma logging of the swelling clay core.

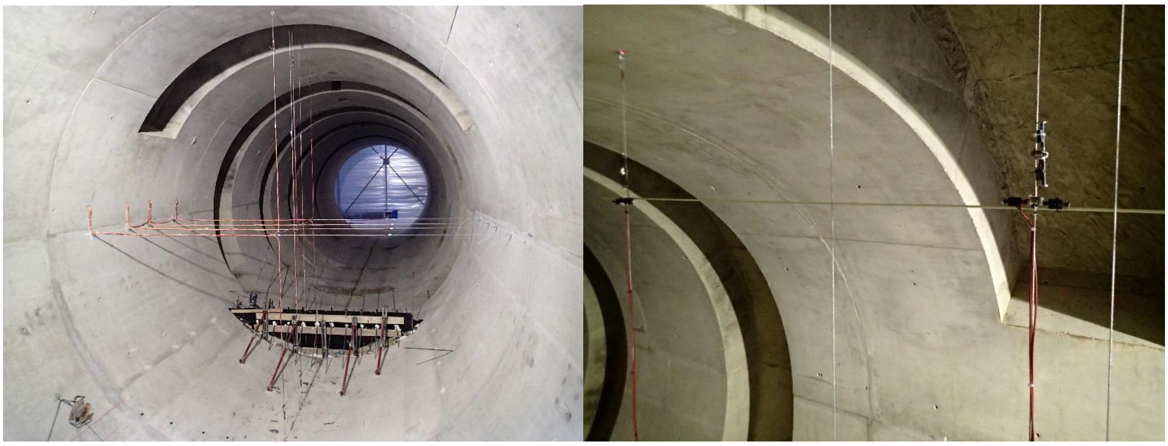

Figure 2.5: Photos of temperature sensors and strain gauges as installed in the test box

SCC and Shotcrete Containment Walls: Compliance with FSSDS02 and FSSDS03

To monitor the temperature, 16 platinum-based resistance thermometers (PT1000 sensors) in four sections for each type of containment wall were used (Figure 2.3). To measure the strain, 18 strain gauge sensors in three sections for each type of containment wall were oriented in the vertical (Figure 2.3) and horizontal directions.

The design specifications for the 2 containment walls concerning temperature and strain are:

- Peak temperature < 50°C (FSSDS02).
- Shrinkage < 350 µm/m at 90 days (FSSDS03).

Example plots showing the measurement of the temperature and strain observed at the Section 1 location (first blue section on the right-hand side of Figure 2.3) for the SCC containment wall and Section 5 (first blue section after the red sections on the left-hand side of Figure 2.3) for the shotcrete containment wall are shown in Figure 2.5 and Figure 2.6, respectively. Measurements at other locations for each containment wall are summarised in Table 2.2 (SCC wall) and Table 2.3 (shotcrete wall).

For the SCC containment wall, the maximum temperature was 48.8°C and the maximum strain was 284µm/m. Therefore, the requirements for the temperature and the shrinkage at 90 days were fulfilled. It appears that shrinkage, in this case, was mainly a thermal process.

For the shotcrete containment wall, the maximum temperature was 66.7°C and the maximum strain was 633µm/m. Therefore, the requirements for the temperature and shrinkage at 90 days were not fulfilled (even if the deviations are minor). The excessive addition of a hardening additive at the time of spraying is currently considered to be the main reason for the shotcrete temperature being higher than expected. Another possible explanation could be the choice of the “B50 CEM I 52.5 Le Teil” cement, which is a very “reactive” component, and may not be ideally suited to shotcrete application in thick multiple layers. The shrinkage value deviation is probably linked to the heterogeneity appearing at the contact between two shotcrete layers when applied by the operator (poor purging of rebounds).

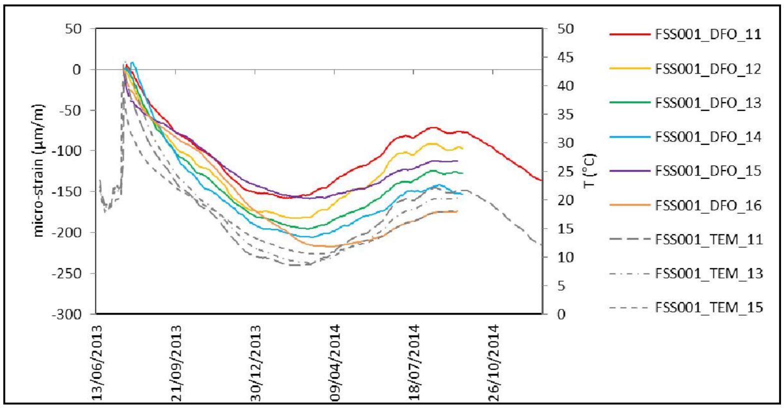

Figure 2.5: Temperature and strain measured for the low-pH SCC containment wall at the Section 1 location.

Table 2.2: Maximum temperature and maximum strain measured for the SCC containment wall.

Location	Maximum Temperature (°C)	Maximum Strain (µm/m)
Section 1	48.8	218
Section 2	47.2	284
Section 3	46.9	Not Available
Section 4	46.1	257

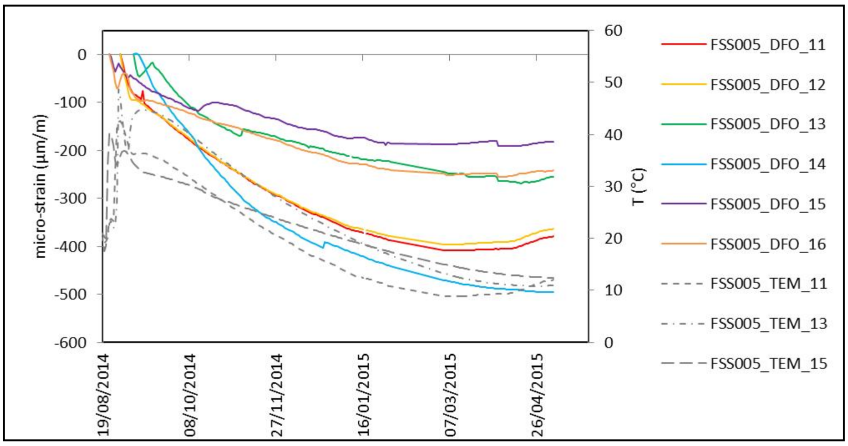

Figure 2.6: Temperature and strain measured for the low-pH shotcrete containment wall at the Section 5 location.

Table 2.3: Maximum temperature and maximum strain measured for the shotcrete containment wall.

Location	Maximum Temperature (°C)	Maximum Strain (µm/m)
Section 5	57.9	495
Section 6	63.7	592
Section 7	66.6	Not available
Section 8	66.7	633

Bentonite Swelling Clay Core: Compliance with FSSDS07

In order to compare the emplaced bentonite mix dry density with the 1620 kg/m^3 (initial) design specification and the new specification (1500 kg/m^3) determined at the end of the metric emplacement tests, the mix density was measured/evaluated using 4 methods:

- Mass balance comparison of the emplaced materials with the internal volume of the part of the test box used for the swelling clay core was carried-out.
- TDR data were collected and also interpreted.
- Penetrometer measurements were collected.
- Gamma-gamma logs were obtained.

In order to provide a comparison with the dry density design specification, the results from the 4 methods were combined as described below.

Mass Balance Estimation of Bentonite Dry Density

The mass balance estimation was carried out as follows:

1. A preliminary 3D scan of the inside of the test box was done at the end of its construction, thus providing an accurate measurement of the total internal volume (including the recesses).
2. In order to calculate the residual volume to be backfilled, this 3D scan measurement was repeated again at various stages of the seal construction:
    - After building of the SCC containment wall.
    - After having backfilled the first two thirds of the swelling clay core.
    - After construction of the bentonite core support wall (made of concrete blocks).
3. For the bentonite materials, each big bag (of pellets) and each octabin (containing the powder) was tagged and weighed before use.

4. The average dry density was calculated for the lower two thirds and upper third of the clay core by dividing the mass of emplaced bentonite by the volume backfilled.

5. The average for the entire core was obtained by averaging these values.

The TDR Measurements

The TDR technology was used to monitor the quality of the core at end of backfilling. This technology was selected for the following reasons:

1. Measurements must be able to detect voids and irregularities in the filling.
2. Measurements have to be non-invasive.
3. Sensors and accessories should not interfere with the filling process.
4. Measurements should be able to resolve small volumes.

The positioning of the TDR sensors inside the test box (periphery) is illustrated in Figure 2.7, while

Figure 2**.8** shows the effective TDR sensors emplacement inside the FSS test box prior to bentonite mix backfill operations.

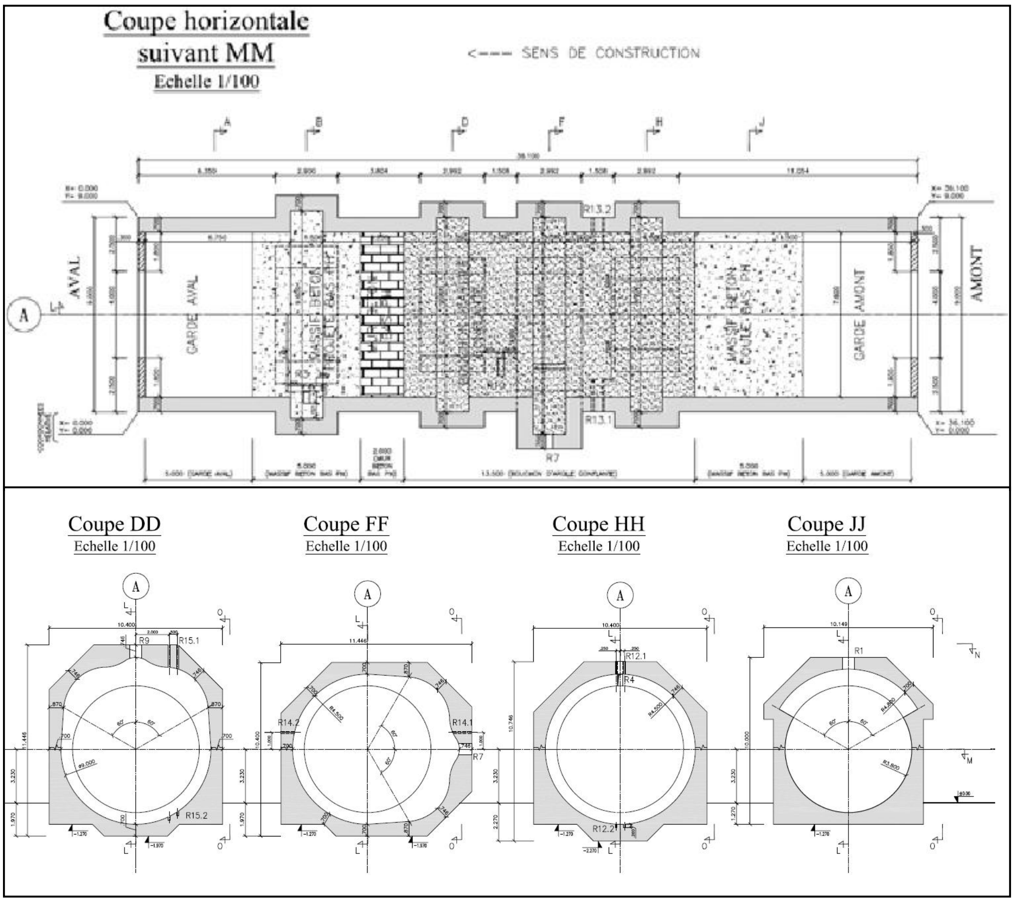

Figure 2.7: Longitudinal (top) and sectional (bottom) positioning of the TDR sensors.

Figure 2.8: TDR sensors emplacement in a recess (left) and at front of SCC plug (right).

As a basis for interpretation of the TDR results, calibration tests were initially carried out as part of the bentonite emplacement quality control. The calibration was performed during the metric emplacement tests, principally carried out to validate the backfilling method.

Figure 2.**9** shows the TDR sensors emplaced inside the metric concrete pipe used for this purpose.

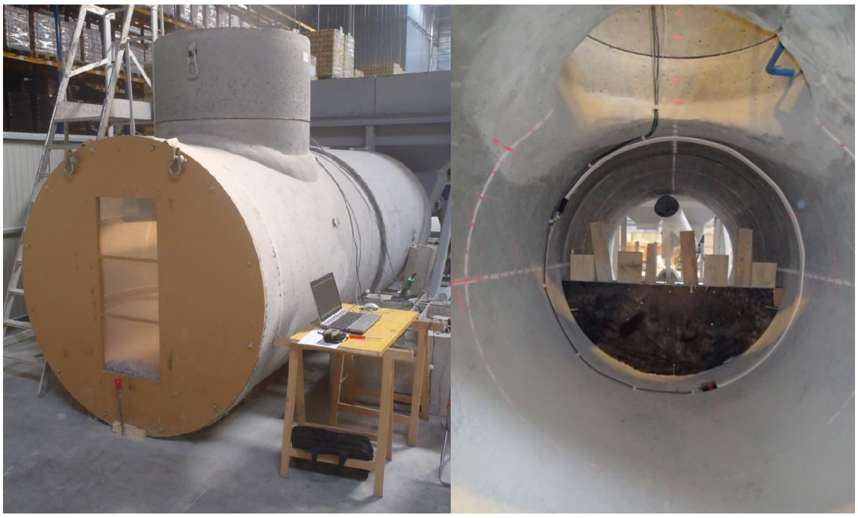

Figure 2.9: TDR sensor calibration inside the metric emplacement test pipe.

The results obtained on sections HH, FF, DD and JJ (see Figure 2.7) are illustrated by images, an example of which is shown in

Figure 2.10 for the HH section. Density values are represented by different colours, reflecting the backfill quality detected by the sensors. The following observations are made:

- The backfill density is optimum in the bottom half of the core with a density higher than 1500 kg/m^3.
- The lower part of the top half of the clay core demonstrates a transition in density with a progressive segregation of the bentonite admixture, with the admixture located higher in the core containing more pellets and less powder.
- The upper part of the top half of the clay core contains local voids, where the bentonite is at least 3 cm away from the TDR sensor.

The penetrometer measurements

After installation of the FSS test, the emplaced bentonite dry density inside the FSS test box was measured using 10 penetrometer surveys with an average depth or length of 8 m. The surveys were oriented vertically, horizontally or oblique, as follows:

- Six vertical tests performed from the upper platform of the test box.
- Three horizontal tests performed from the side of the test box.
- One oblique test performed from the upper platform of the test box with an angle to the horizontal of approximately 45°.

The length and depth of the different penetrometer tests are summarised in

Table 2.4.

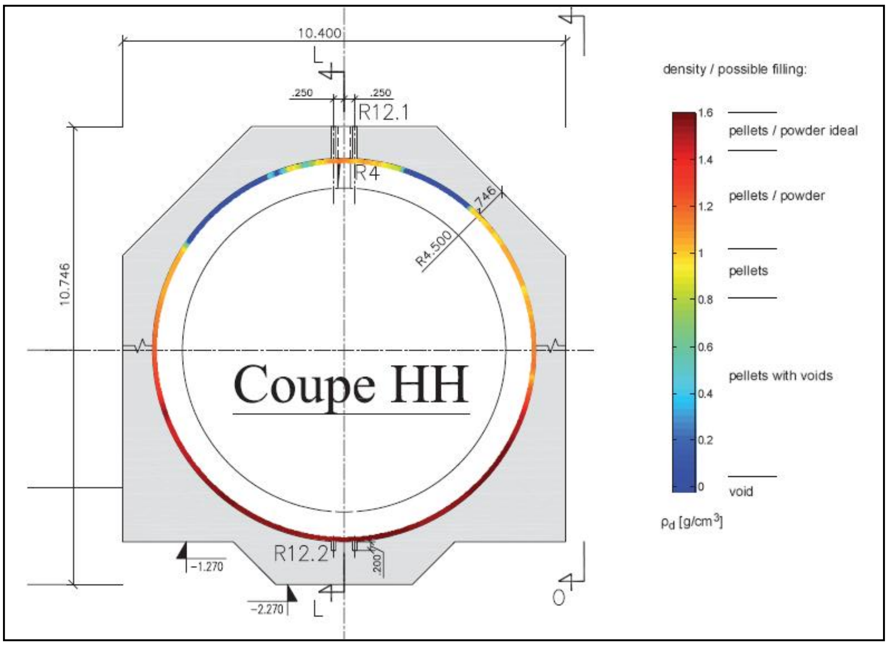

Figure 2.10: Illustration of TDR sensors measure of dry mix density at the HH section.

Table 2.4: The ten penetrometer tests performed on the emplaced bentonite in FSS.

N°	Orientation	Angle with respect to the vertical axis (°)	Depth of the penetrometer survey (m)	Length of pre-drilling (m)	Length of material passed through (m)
SV1	Vertical	0	8.50	0	8.50
SV2	Vertical	0	8.87	0	8.87
SV3	Vertical	0	7.24	0	7.24
SV4	Vertical	0	7.60	0	7.60
SV5	Vertical	0	6.65	1.50	5.15
SV6	Vertical	0	8.28	0.70	7.58
SH7	Horizontal	90	8.79	0.70	8.09
SH8	Horizontal	90	7.86	0.70	7.16
SH9	Horizontal	90	8.67	0.70	7.97
SO10	Oblique	45	13.56	1.00	12.56

As a basis for interpretation of the penetrometer test results, calibration experiments were carried out as part of the bentonite emplacement quality control. The calibration was performed for the five mixtures of pellets and crushed pellets defined in the specification for the FSS experiment. These concern the following mixtures:

- 100% Pellets.
- 100% Crushed pellets.
- 70% pellets and 30% crushed pellets as used in FSS.
- 85% pellets and 15% crushed pellets.

- 55% pellets and 45% crushed pellets.

For each mixture, five samples with a different density were prepared. For the optimal FSS mix 70:30, densities were centred around 1500 kg/m^3, consistent with the target value of FSS (at a scale of 1:1). Penetrometer tests were then performed on each sample to measure the resistance of the material (in MPa). The relationship between the dry density and the resistance for a given material is defined by a logarithmic function. From the different calibration tests, a linear regression curve of the logarithmic relationship between the resistance value and the dry density for each material was produced (Figure 2.11). An illustration of a calibration test is shown in Figure 2.12 below.

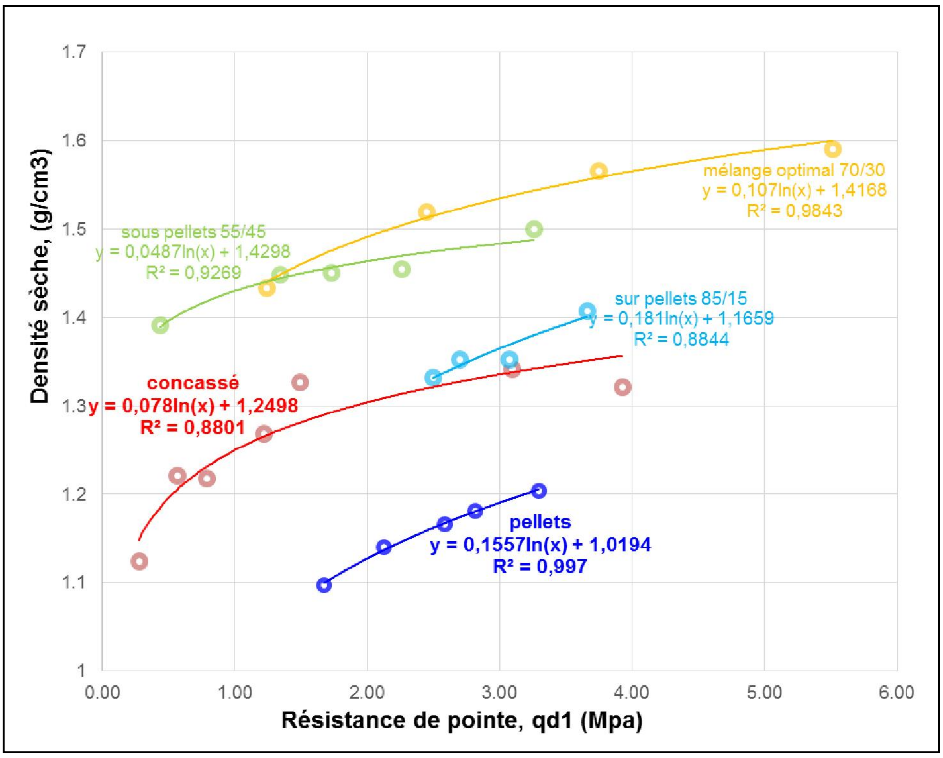

Figure 2.11: Calibration curves for the five bentonite mixes tested. "Densité sèche" means "dry density", "mélange" means "mix", "concassé" means "crushed", and "Résistance de pointe" means "resistance of the tip" of the penetrometer.

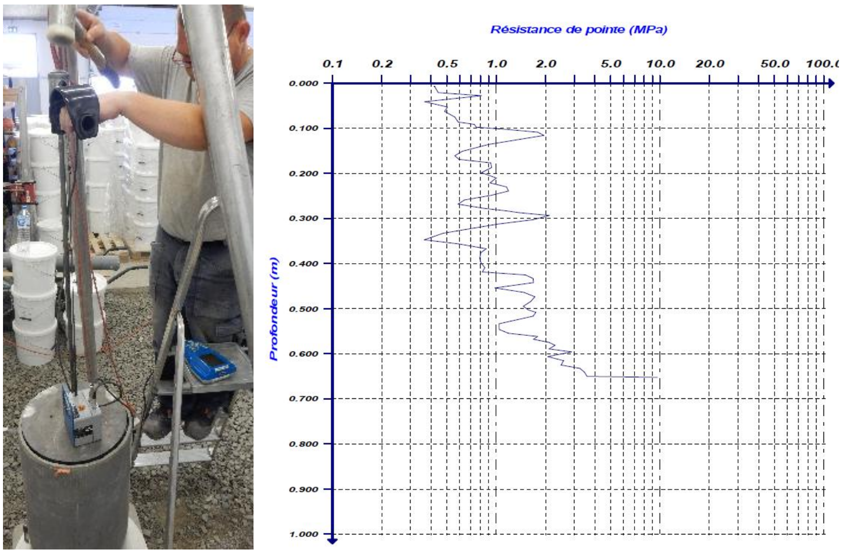

Figure 2.12: Calibration test on FSS 70/30 mix (left) and related penetrogram (right)

The application of these calibration curves to determine the spatial variability of the bentonite admixture dry density inside the core is ongoing. Additional work is envisaged to validate results and conclude whether this penetrometry device is a routine “commissioning tool” for the future Cigéo operations.

From a qualitative point of view, the penetrometer surveys have also shown that the bentonite dry density is higher in the lower parts of the core than in the recesses at the top of the test box. This point was “qualitatively” confirmed by observations through the polycarbonate windows positioned on the top, on the sides and at bottom of the test box. The spatial variability in the bentonite dry density is the result of segregation of the admixture as the bentonite is emplaced. In summital recesses (at the top of the test box), only the pellets are present, while the mix is homogeneous at the bottom of the core with no visible inter-pellets voids.

Gamma-gamma Logging

The same conclusion, as for the penetrometer results, can be drawn from the gamma-gamma logging campaign: the technology is not mature enough to provide “validated” quantitative measurements of the bentonite dry density. From a qualitative point of view, however, the gamma-gamma logging also identified vertical segregation of the bentonite mix between the bottom part of the core and the recesses at the top of the test box.

General conclusions on the evaluation of the quality of bentonite emplacement

At this stage of research and development, no proven (qualified) tools have been found to accurately determine the dry density of the core bentonite mix and its spatial variability. Additional work is needed in this area.

The gamma-gamma logging tool cannot be a commissioning tool adapted to the *in situ* operations in Cigéo, since pipes cannot be installed and left inside the real and final core. At this stage, additional work is (so far) not contemplated on this technology.

The same can be said of the TDR devices (however this technology could be again explored in the full scale demonstrators scheduled in the Cigéo Pilot phase – 2025/2034).

On the contrary, the penetrometer can be handled underground for horizontal and oblique investigations inside the core volume. Andra is considering further development for future use in Cigéo.

Practically, the most adapted/reliable method to check the density compliance remains the combined use of 3D scanning and mass balance, even if this method only provides average values and no details on homogeneity.

The segregation phenomenon noticed in the summital recesses is deemed a marginal point in the swelling clay core behaviour, as the homogenisation of the clay core is expected to increase with saturation. The results of the REM experiment will be very helpful in confirming this expectation.

One practical conclusion from the FSS Experiment is that if additional backfilling of the recesses at the top of the clay core is required in the real Cigéo operations, it is practical to locally use shotclay technology, as practiced in the Czech EPSP experiment within DOPAS. Using such technology, small volumes of bentonite spray can be easily and accurately emplaced into pre-identified residual voids.

2.4 Evaluation of the Results from Dismantling of FSS

In this section the observations made at the time of dismantling of the FSS experiment are summarised.

- The survey and the nature of cracks as observed at the surface of the sawn sections in the two containment walls are first described;
- The quality of 2 low pH concrete monoliths is then discussed.

The dismantling activities of the FSS experiment, which took place between August 2015 and December 2015, are illustrated in Figure 2..

(a) Coring of the wire sawn low-pH SCC concrete containment wall

(b) Coring of the wire sawn low-pH shotcrete containment wall

(c) Demolition of the low-pH shotcrete containment wall

(d) Demolition of the low-pH SCC concrete containment wall

(e) Removal of the bentonite clay core

(f) Emplacement of bentonite in bags for recycling

Figure 2.13: Activities undertaken during the dismantling of FSS (2015).

The dismantling of FSS included coring of the two containment walls. Core samples of 40cm diameter were taken from the low-pH SCC and shotcrete containment walls for further analysis and observation (Figure 2. (a) and (b)).

After completion of analysis and investigations, the shotcrete and concrete walls were dismantled. This included sawing the shotcrete containment wall longitudinally (i.e., along the test box length) and sawing the SCC containment wall transversally, before demolition using a digger. (Figure 2. (c) and (d)).

During the dismantling, the bentonite core material was removed and placed in bags for recycling (Figure 2. (e) and (f)).

The aim of dismantling was to carry out the following investigations on the containment walls:

- Visual inspection and laser measurement of cracks in the concrete containment walls.
- Measurement of surface hardness and sonic velocity to characterise the quality of the concrete.
- Characterisation of surface hardness using an electronic type sclerometer "SilverSchmidt".
- Sonic auscultation using a PUNDIT PL- 200 PE Proceq device to determine the sonic velocity, the crack depth, and the existence of defects.

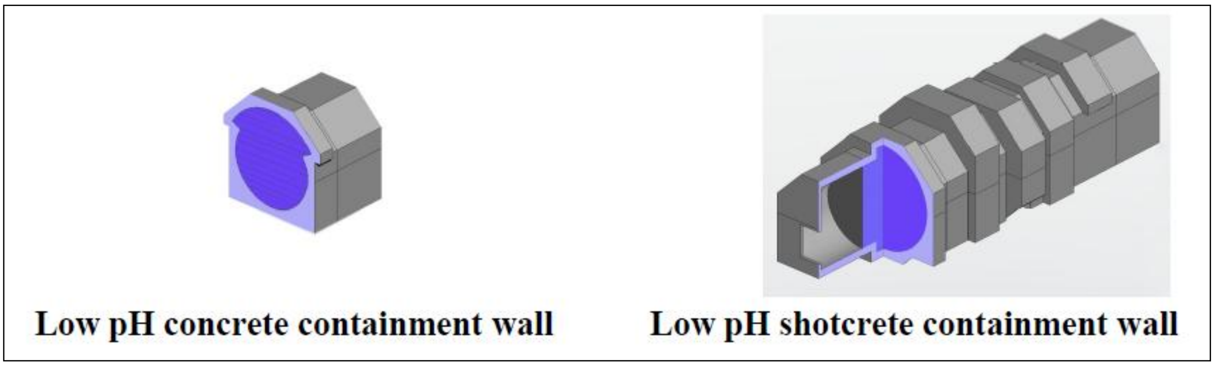

Figure 2.14: Sawing of the SCC containment wall (transversally, left) and the shotcrete containment wall (transversally and longitudinally, right) in the dismantling activities of FSS.

Survey of Cracks in Monoliths

Crack length, aperture and depth were measured at high precision using a laser. The laser was controlled from a scaffold via a touch pad. Figure 2.12 shows the cracks identified in the 2 containment walls. Subsequently, the cracks were mapped, but the accuracy of the mapping was affected by the presence of the scaffold pipes and platforms.

For the low-pH SCC wall, the main observations were:

- Microcracks were identified. Their extent (a centimetric penetration) and size (a millimetric width) were quite limited and of no structural impact on the concrete monolith.
- A microcrack was present on the entire perimeter of the SCC containment wall at its interface with the test box. It could not be determined if this microcrack was “penetrating” or simply a surface artefact. In Cigéo, this type of microcrack, if it appeared, would have no practical impact. The progressive rock creeping would lead to a progressive convergence of the drift liner and this convergence phenomenon would have a fretting effect on the SCC containment wall. Besides, the containment wall geometry is dimensioned based on its interaction with the host rock, not by its friction with the liner wall.
- As mentioned in DOPAS Work Package 3, Deliverable D3.30 “WP3 Final Summary Report “Summary of, and Lessons Learned from, Design and Construction of the DOPAS Experiments”, White *et al.* (2016), only a few litres of contact grouting (less than 100 litres) were injected at the end of the SCC containment wall casting. This grout was locally (less than one square foot) visible and only at the very upper part of the wall, showing a good bonding effect.
- The different concrete pouring passes were not seen (which confirms a good adherence between layers).
- Porosity variations in height were not significant, as confirmed by later (in lab) measurements on concrete cores.

For the shotcrete containment wall, the following observations were made:

- A microcrack was present on the entire perimeter of the shotcrete, at the exception of the upper part of the demonstrator where the two concretes (OPC concrete box and low-pH shotcrete) seem attached.
- The different layers of shotcrete were visible with variations in density.
- Porosity variations were more significant in the lower part, as confirmed by later (in lab) measurements on shotcrete cores.

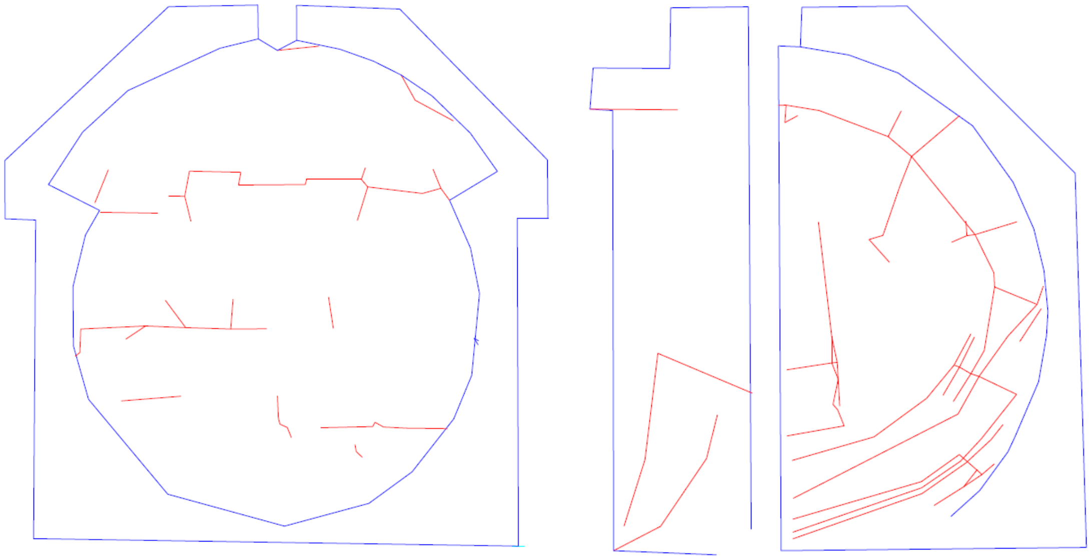

Figure 2.12: The pattern of cracks in the low-pH SCC (left) and shotcrete (right) containment walls.

Note that the different patterns of cracks in the SCC and shotcrete walls could be linked to the way the two types of concrete were cast. The SCC was cast in horizontal layers, whereas the shotcrete layers were applied in a hemispherical shape (onion layer type of shape).

Concrete Quality: Surface Hardness and Sonic Velocity

For concrete, it is established that the bouncing height of an object on concrete increases as the surface hardness reaches higher values (which corresponds in principle to a stiffer concrete). A sclerometer based on this principle was used to measure the hardness of the concrete and shotcrete walls. The sclerometer comprises a flyweight projected by a spring along a rod for transmitting the force to the concrete. The velocity of the piston is measured by the device to determine a rebound number. The rebound number can be processed to estimate the concrete compressive strength through corresponding functions which take into account the type of material, carbonation, and various test conditions. The Figure 2.13 presents the results for the strength (in MPa) of the concrete and shotcrete containment walls.

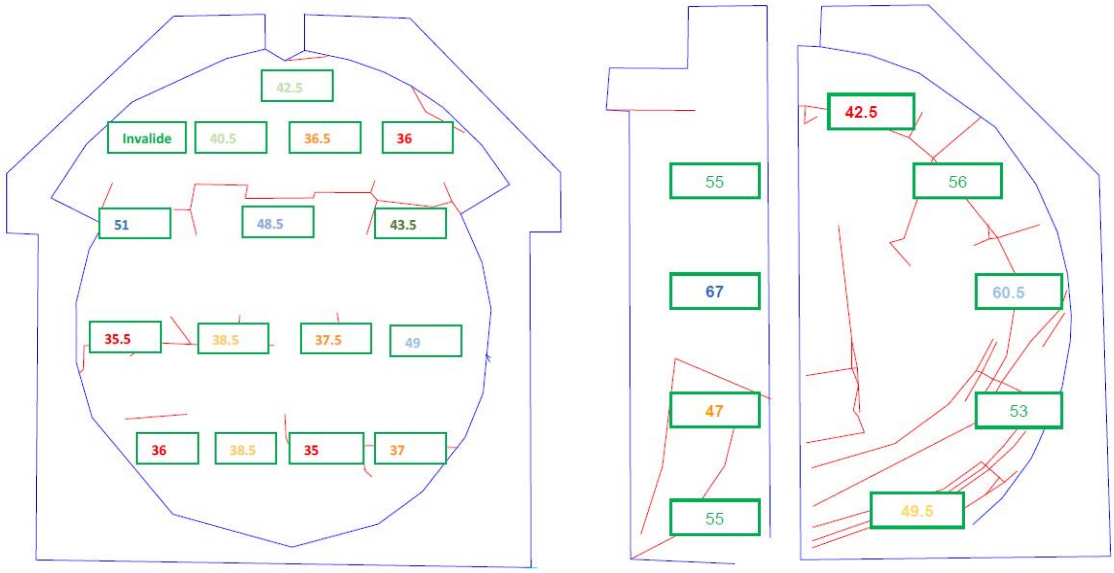

Figure 2.13: Results for hardness tests on the concrete (left) and shotcrete (right) containment walls (numbers indicate values in MPa).

Various measurements were performed to determine the sonic velocity and the existence of defects in the concrete and shotcrete walls. Typically, a concrete can be considered of good quality with a sonic velocity of approximately 4000m/s.

The sound propagation speeds measured varied between 2257 m/s and 3968 m/s. These low velocities were obtained due (most likely) to the local presence of a microcrack on the line of the measurements, creating an artefact.

In the SCC wall, the cracks were found to be neither perpendicular nor parallel to the surface and of limited extent, confirming the observations made by laser meter. In the shotcrete wall, a crack depth of up to 5.5 cm was estimated, confirming the heterogeneity of the shotcrete containment wall.

Note that the determination of the physical and chemical properties of the cores taken from the two types of concrete walls is still on going, in various laboratories, at time of writing of this report. All these preliminary results are however coherent with the observations made on the two wall sections. SCC is homogeneous while the variability of shotcrete is quite significant. The concrete mixes and the emplacement methods are the main causes of the differences observed.

3 Evaluation of the FSS Measurement and Monitoring Systems

This section describes the lessons and preliminary conclusions that can be drawn with regards to the measurement and monitoring systems used in the seal components of FSS.

3.1 Measurement systems for the concrete containments walls

Low-pH SCC and shotcrete shrinkage and curing temperature sensors worked well. They could be kept in the Cigéo containment walls as a quality control tool. Intrusive monitoring is not an issue in this case, since the containment walls have no hydraulic performance requirements in the Cigéo seal concepts.

Evaluation of quality of the contact between the host rock and the concrete is challenging. Measuring the volume of injected bonding grout is an indicator of the residual volumes to be filled. Practically, it is probable that 3D scanning before and after casting a containment wall will be the carried out and compared with the measurement of the concrete volume poured inside the form. Besides, the progressive creeping of the rock will ensure a full contact with the concrete before the core swelling induced forces take place, minimising this issue.

3.2 Measurement systems for the swelling clay core

Two issues are of concern to commission the swelling clay core:

- Compliance of the measured average dry emplaced density of the bentonitic mix with the specified requirements (at scale of seal).
- Assessing the space variability of the emplaced bentonitic mix in the core volume to determine the backfilling heterogeneity, even if no variability parameters have been defined so far by Andra.

On the basis of the works carried-out in FSS, Andra's conclusions on the monitoring / commissioning tools deployed are as follows:

- Penetrometry is a promising solution but is far from ready for application (as calibration is bentonitic mix specific, and should be reconsidered for oblique and longitudinal applications). Andra will further explore its development in the future, in particular for the full scale seal demonstrators in the Cigéo Pilot phase (2025-2034).
- Observation windows: visual observation was difficult at times due to dust build-up on the polycarbonate folio. From a qualitative point of view, they confirmed the deductions made on heterogeneity from gamma-gamma logging and the TDR sensors. These observation windows will of course be of no use in Cigéo.
- Consistent results from gamma-gamma logging need additional development and a better calibration. Besides, logging requires pipes inside bentonite core, including organic materials. This intrusive application to the real Cigéo seals is not considered and no further development is envisaged at this stage, unless Andra is required to do so.
- For operations, mass weighing of bentonite and 3D scanning will be used in Cigéo.

- No non-intrusive solutions to estimate residual voids have been identified so far. Using the TDR technology is intrusive, even if much less space is needed than for gamma-gamma logging. Andra has not decided yet if this TDR technology will be deployed for the real Cigéo seals or the full scale demonstrators (Pilot Phase).

Table 3.5: Qualitative evaluation of the FSS experiment monitoring system and of DAS.

Sensor	Parameter(s)	Evaluation
PT1000	Temperature	The sensors were able to track the temperature evolution in various sections of the 2 low pH concrete monoliths.
Vibrating cable Geokon 4200A-2	Strain in the 2 types of concrete walls	The sensors were able to track the deformation/strain development in the plugs. Most sensors were able to withstand shotcreting or concrete casting. One section of sensors did not provide data in the SCC monolith (same situation in the SCC). No possibility to say if the failure is due to sensor damage, cabling damage or poor cabling at start-up (QA/QC to be improved in Cigéo repository operations).
TDR Solexperts CSI635_plus	Measure of Dry Mix Density	All the sensors worked well and were capable to evidence the bentonite mix density variation (segregation) at ceiling, as confirmed by other investigation tools and observation windows.
Server	**Data collected**	**Evaluation**
Local DAS (Data Acquisition System) by GeoMonitor	See above + Topographical evolution of test box during filling operations + Registering of videos during operations + Relative Ambient Humidity + Relative Air Temperature	Worked very well, no flaws noticed. DAS was connected via FTP site with Andra Central Data Acquisition System (by SolData), for redundancy in acquisition. Similar approach considered for future Cigéo operations.

4 Progress on Monitoring, Investigation and Commissioning aspects and remaining Technical Developments

This chapter discusses the progress that has been made (and the remaining improvements) on the technical feasibility of commissioning and monitoring the Cigéo repository seal component, based on the experience derived from the FSS experiment.

Note: The phenomenological issues related to the progressive core saturation (monitoring of swelling pressure, homogenization, density…) are not dealt with, since they belong to the scientific rationale which has been covered in the REM experiment (cf. D4.2). They furthermore imply a time scale (thousands of years) which is not commensurate with operational considerations as debated below.

4.1 Monitoring Systems

The full-scale experiments undertaken in the FSS experiment have utilised a range of sensors to monitor a series of common parameters, for example:

- Temperature in concrete.
- Total pressure and pore pressure (applicable to REM, not to FSS).
- Strain and displacement.
- Air relative humidity.
- Air ambient temperature.
- Topographic evolution of test box.

In general, the sensors have operated as expected and allowed monitoring of the performance of the seal components with respect to the design specifications that have been set, and also the overall performance with respect to the safety.

The FSS experiment has also demonstrated that monitoring of the seal components in the repository is feasible and might produce relevant data. Their relevance and applicability is discussed further.

Relatively detailed monitoring systems have been used to track the performance of the FSS seal components and to demonstrate their consistency with requirements. However, any monitoring of seals in Cigéo will have to be significantly reduced in scale to allow disposal to be achieved efficiently and effectively. Introduction of large numbers of monitoring sensors into Cigéo seals could affect both the post-closure performance of the system and the schedule for their implementation. Therefore, there is a need to identify what relevant monitoring data must be acquired to provide further confidence in repository performance or to respond to specific stakeholder requirements. The same is true for investigation of components as built.

4.2 The Wall/Core-Rock Interface

The experience from the FSS experiment has shown that grouting of the wall-rock interface is an important step in the successful implementation of a seal. Routines are required that reduce the need for grouting of the interface. This can be helped by a better mass-balance compilation of the materials emplaced (first the concrete, then the grout).

4.3 Industrialisation in Cigéo

The FSS experiment has contributed towards demonstration of the technical feasibility of seals in Cigéo. However, the results of the experiment need to be used in the development of industrial solutions for installing many tens of seals in the future. Industrialisation requires collation of construction procedures and quality control procedures that can be used to safely construct plugs and seals with reproducible structures and processes and also with high reliability. This is true in particular for commissioning the seal components and monitoring them.

Industrialisation will require the transfer of the lessons from the full-scale seal (FSS) experiment to the repository. This may involve further full-scale testing of revised reference designs in the repository (the full scale demonstrators planned in the pilot phase will be of concern) to demonstrate compliance of the final design prior to award of an operation licence (or a closure license in the case of Cigéo). Industrialisation also needs to consider the availability of rugged and well-proofed technologies in the future (i.e. decades later), in particular for the instrumentation required to directly monitor seal components, and how these data will be used in future decision making (first for commissioning them).

Dimensioning of all related facilities based on practical experiences and available equipment is one important part of future work of all WMOs and of course of Andra It is important to study the whole operation sequence. This is one learning point from DOPAS experiences as well. The transposition to Cigéo is described below.

1. Investigation and Monitoring of the 2 Concrete Monoliths

The monitoring system (**temperature and shrinkage sensors**) installed inside the SCC/shotcrete containment walls was able to reliably monitor the curing temperature and shrinkage of the two types of low pH concrete:

- The curing temperature and shrinkage in the self-compacting concrete (SCC) containment wall was less than what was specified (i.e. were compliant with requirements);
- Conversely, requirements were not fully met for the shotcrete.

These sensors look fit for future use in Cigéo, even if their installation is intrusive: their wiring implies passing through the concrete monoliths, but this is of no structural/mechanical impact on the containment walls, while the potential hydraulic by-pass thus created is of no consequence, since the abutments have no hydraulic function in the reference seal concept.

Investigation of the concrete monoliths was carried out by wire sawing, photography, and sonic survey and coring.

- Wire sawing cannot be repeated on a monolith which must preserve its mechanical functions, but photography (mapping of the monolith visible face) is a good and relatively straightforward way to look at the concrete homogeneity, to evaluate the quality of contact between 2 cast/sprayed layers or between the monolith concrete and liner concrete walls (same for the contact grouting). Mapping of cracks (width, extension) can also be carried out, as well as sonic survey, to investigate the cracks depth if doubt arises about the cracks penetration. These operations are however time consuming and do not provide enough information on the concrete quality deep inside the wall. Additional investigation systems may have to be explored if the structural integrity of the monolith is at stake (e.g. in case shrinkage or temperature values (as measured by the monitoring system) are not compliant with the performance requirements specified).
- Coring (combined or not with sawing) of the concrete monoliths was used as an efficient mean of investigation during post-mortem dismantling of FSS. This method cannot be generalized to routine operations in Cigéo. One may however decide to core a seal monolith in Cigéo, but up to a certain extent (this action will have to be debated with (and agreed by) the nuclear authority or its TSO), if doubt arises about the monolith compliance (see example above about non-compliance of concrete temperature or shrinkage values).
- A good cross checking between the mass balance (hence the volume) of the concrete poured (sprayed) and the volume to be backfilled will help to evaluate if any significant void are left unfilled. The same can be done for contact grouting operations.

2. Investigation and Monitoring of the Bentonite Core

The **time domain reflectometer** (**TDR sensors**) device installed inside the test box provided qualitative information on the space density variation and homogeneity of the bentonite backfilling, in particular for the core summital recesses. As anticipated, residual voids appeared and segregation of the bentonite admixture occurred. This TDR system still needs further calibration. It could be considered in the construction of the future full scale seal demonstrators planned in the Cigéo Pilot phase. However, TDR technology will most likely not be incorporated in the making of the real Cigéo seals, since its installation inside the core is intrusive (unless reliable and lasting wireless methods are developed by that time).

The **gamma-gamma** logging tool, run through pre-installed pipes positioned inside the swelling clay core volume, has qualitatively confirmed the presence of residual voids and evidenced segregation of the bentonite admixture in the summital recesses. This technology needs also additional calibration work to be an effective (i.e. capable of providing quantitative data) measurement tool. Besides, this logging tool must be run inside pre-installed pipes only, which is by nature an intrusive solution. At this stage, this TDR monitoring system is not considered fit for use in Cigéo, but its opportunity of use may be re-envisaged for the full scale demonstrators planned during the Cigéo pilot phase (i.e. 2025-2034).

The **penetrometer** tool deployed by Andra before dismantling FSS was the most satisfactory system tested so far to evaluate the space variability of dry emplaced density of the bentonitic mix backfilled in the drift model. It provided quantitative data. Even if the calibration has to be improved and is specific of a given bentonitic mix, this technology is deemed as the most promising and most handy device for commissioning the swelling clay core at the end of the core construction.

The **mass balance approach** used to evaluate the average dry emplaced density of the swelling clay core consisted in confronting the initial/residual volumes to be backfilled with the bentonitic mix vs the cumulated mass of pulverulent material already emplaced. This approach turned out to be effective and straightforward. The main improvement identified is the need for a more efficient (faster) 3D scanning system, providing "on time" data on the residual volumes to be backfilled.

3. Data acquisition system (DAS)

The Local DAS (Data Acquisition System) by GeoMonitor was installed at vicinity of the test box, to register the values measured by sensors (concrete hardening temperature and shrinkage values, TDR data).

It was also used for the collection of other operations linked parameters, such as the topographical evolution of test box during filling operations, the registering of videos taken during operations, and finally the ambient air relative humidity and air temperature values.

This DAS system worked very well, no flaws noticed. It was connected via an FTP site with Andra's Central Data Acquisition System (by SolData), for redundancy in acquisition.

This approach, already implemented by Andra for monitoring various scientific experiments in the Bure URL infrastructures, turns out to be quite effective. A similar approach is considered for future Cigéo seal construction operations.

4.4 Conclusions

The FSS experiment has demonstrated that it is feasible to industrially build a horizontal seal system in the Callovo-Oxfordian host rock considered for the French Cigéo repository. This demonstration has included verification of compliance of the seal components as built, thanks to the monitoring systems and investigation methods deployed for commissioning purposes.

The list of acceptance criteria (those which will be declined in quantitative parameters with contractual tolerances for commissioning the seal components) has still to be formalized.

Concerning the monitoring and investigation tools potentially deployed for commissioning, one must say that for most of them, there is still a need for additional development (e.g. calibration) or specific adaptation (they must be user's friendly) to the objects built, before a "qualification" is granted to the commissioning tools concerned.

These further developments/improvements and the qualification steps will have to be scheduled well ahead of underground operations, when planning the future Cigéo closure activities and first of all before the construction of full scale seal demonstrators as envisaged during the Cigéo pilot phase (i.e. 2025-2034).

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