DOPAS Work Package 4 Deliverable 4.8
FSS Experiment Summary Report

Grant Agreement No:	323273
Authors:	Aurélien Noiret, Sandrine Bethmont, Jean-Michel Bosgiraud and Régis Foin (Andra)
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APPROVED FOR SUBMISSION:

Johanna Hansen - ***31.8.2016***

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 in the period September 2012 – August 2016. Fourteen European WMOs and research and consultancy institutions from eight European countries are participating in the DOPAS Project. The Project is 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 the project.

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. The Project is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination and is led by Posiva, Finland. 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 the DOPAS Deliverables.
- 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 is Deliverable D4.8 of the DOPAS Project, and is part of WP4. This work package addresses the performance evaluation of the full-scale experiment FSS in the DOPAS Project. Deliverable D4.8 is the "FSS Experiment Summary Report". The objectives are to provide an integrated "state-of-the-art" summary of the outcomes of FSS at the end of the DOPAS Project with respect to its ability to meet the safety functions specified in Andra's disposal concepts (in Cigéo), and to present the technical and operational issues that have been resolved or evidenced in this experiment and those still outstanding.

The report addresses the following questions and topics:

- What has been learnt to date in the FSS experiment about the ability of seals designs to meet safety functions specified in Cigéo?
- What technical and operational issues have been resolved and how?
- What outstanding technical and operational issues remain?
- What is the current status regarding the technical feasibility of installing the reference seal design in Cigéo to meet the requirements in the design basis and what modifications are necessary to achieve technical feasibility?

In the DOPAS Project, a distinction has been made between reference and experiment designs:

- The term "reference design" is used to denote the design of a plug/seal within a disposal concept, i.e., the design used to underpin the safety case or licence application.
- The term "experiment design" is used to indicate the design of the plug/seal being tested at full scale in the DOPAS Project.

In this report, the design basis work undertaken in WP2 (cf. D2.3 "Strategies of demonstrating conformity of reference design to design basis" White *et al.*) has provided a basis for the method used to evaluate the performance of the FSS experiment and the content of the requirements evaluated. The design basis for the FSS experiment includes many design specifications, and it is outside the scope of this report to systematically evaluate the performance of the experiment against each design specification. Therefore, instead of an evaluation of performance against safety functions, performance has been evaluated against a set of “key design specifications”.

The main properties common to the FSS experiment design specifications are summarized below are:

- Concrete strength;
- pH of concrete leachate;
- Curing temperature of concrete;
- Density/swelling pressure of dry emplaced bentonite.

The FSS experiment design and construction is described in Deliverable D3.1 “FSS Experiment Construction Summary Report” Bosgiraud *et al*. which belongs to WP3 of DOPAS.

Performance Evaluation of the Experimental Work 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 by two low-pH concrete containment plugs. Andra tested two types of low-pH for the containment walls: low-pH self-compacting concrete (SCC) and low-pH shotcrete.

The FSS experiment is focused on the construction of the seal components. Therefore, the bentonitic materials forming the swelling clay core were not saturated or otherwise pressurised to check the swelling pressure and hydraulic conductivity. Complementary experiments (REM in particular, cf. WP 4 Deliverable D4.2 “Report on bentonite saturation test” Conil *et al.)* were undertaken (in parallel with FSS) to address these issues.

Performance of the monitoring equipment during construction works and bentonite emplacement was good (cf. WP4 Deliverable D4.1 “Report on qualification of commissioning methods” Noiret *et al.*). The monitoring system installed inside the plugs was able to reliably monitor the curing temperature and shrinkage of the two types of concrete.

The curing temperature and shrinkage in the SCC wall was less than what was specified (i.e. were compliant with requirements). Conversely, requirements were not met for the shotcrete, owing to the influence of a hardening additive, which was incorporated in the concrete mix at the time of spraying (another explanation could be the choice of a CEM1 type cement, which is a very reactive material). The time domain reflectometer (TDR) device installed inside the test box provided qualitative information on the density and homogeneity of the bentonite backfilling of the summital recesses. As anticipated, residual voids and segregation of the bentonite admixture occurred. These effects were more significant in the upper third of the core, where mechanical interference between the backfilling machine boom and the core supporting wall prevented a thorough transfer of bentonite material into the recesses. Improved techniques for filling the upper parts of the core can be readily implemented by modifying the boom and/or using other emplacement technique like “shotclay” (i.e. wet bentonite spraying with an air gun).

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 includes verification of practical aspects such as logistics and arranging of concurrent activities. Health and safety issues for workers have been identified and mitigation solutions proposed for the future real case (underground). The operational time needed to build a seal (once the site preparation is completed) is also better estimated at around three months. This is of interest when planning the future Cigéo closure operations and first of all the construction of full scale seal demonstrators as envisaged during the Cigéo pilot phase (i.e. 2025-2034).

Conclusions

WP2, WP3 and WP4 of the DOPAS Project have included:

- Collation of the design basis for the plugs and seals considered in the DOPAS Project (including FSS for Andra), conceptual and basic designs, and the strategy adopted in for demonstrating compliance with the design basis.
- Detailed design, site selection and characterisation, and construction of the experiments (cf. WP3 Deliverable D3.1 “FSS Construction Summary Report” Bosgiraud *et al.*).
- Evaluation of the performance of the full-scale experiments and evaluation of the conclusions from the experiments conducted in the DOPAS Project with respect to the technical feasibility of constructing the reference designs. In this report, the evaluation is about the FSS experiment only.

The experimental programmes undertaken in the DOPAS Project have been successful. For FSS the performance evaluation has been in response to monitoring during installation of the seal components. FSS had to respond to challenges during the conduct of the experimental work, and this illustrates the need for flexibility during the planning for full-scale tests and demonstration work in the Cigéo pilot phase.

The FSS achievements in the DOPAS Project include the following:

- Development of a structured approach to requirements hierarchies applicable to all waste management programmes ;
- Development of a structured approach to development of designs in parallel with development of the design basis (concurrent design) ;
- Application and assessment of techniques for construction of plug/seal slots to high specifications ;
- Successful demonstration of the application of a low permeability bentonite swelling core in the FSS experiment ;

- Successful demonstration of the application of low-pH concrete containment walls, utilising either SCC or shotcrete ;
- Further development of low pH contact grouting materials ;
- Addressing concerns regarding health and safety by modifying proposed bentonitic materials emplacement processes;
- Addressing issues with logistics and project management to successfully construct plugs and seals within the timeframe of the Project.

In addition, the FSS work in the DOPAS Project has allowed consideration of the remaining issues associated with plug/seal design and the next steps in industrialisation of plug/seal installation.

Key recommendations for further works that have been identified include:

- Use of the results from the FSS experiment to revise reference designs for seals in Cigéo, and to consider the compliance of the revised design with the design basis;
- Further clarification on the requirements on the rock adjacent to the seal components to support the siting of the structures (e.g., in a clay formation, the dimensioning of the concrete plug/wall is at stake);
- Evaluation of the requirements on emplaced bentonitic material homogeneity and greater understanding of homogenisation processes for bentonite swelling cores used as part of the seal components designs ;
- For the SCC type of low pH concrete, optimisation of delivery routines and logistical issues needs to be considered as part of the industrialisation of plugging and sealing ;
- For the shotcrete type of low pH concrete, improved mixes and delivery methods as well as better emplacement process (e.g. reducing rebound to ensure a more homogeneous product) are required before application in Cigéo ;
- Undertaking work to industrialise the process of seal construction, including development and documentation of emplacement processes (in summital recesses in particular) and improving quality control programmes.

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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This report is Deliverable D4.8, and is the FSS Experiment Summary Report in WP4. This work package WP4 addresses the appraisal of the full-scale experiments implemented in DOPAS.

1.2 Objectives

The objectives of this report D4.8 are to provide an integrated state-of-the-art summary of the outcomes of FSS, including the main FSS related findings as identified in WP2 and WP3, to evaluate the performance of the containment walls and of the swelling clay core with respect to their ability to meet the safety functions specified in Cigéo, and to present the technical and operational issues that have been resolved in this experiment. This report provides an integrated summary of the progress in design, site selection and characterisation, construction, monitoring and performance, in relation to plugs and seals considered in waste management programmes. The report describes the progress at the time of writing (as defined below) and addresses more particularly the following questions and topics:

- What technical and operational issues have been resolved and how?
- What outstanding technical and operational issues remain?
- What is the current status regarding the technical feasibility of installing the reference Cigéo seal design to meet the requirements in the design basis and what modifications are necessary to achieve technical feasibility?

1.3 Scope

Link to other main DOPAS and FSS related Deliverables

This report (D4.8) is part of a series of WP-level Summary Reports describing the integrated 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 outcomes from FSS 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 are complete and published.

The other WP-level summary reports are:

- D2.4, the WP2 Final Report: “Design Basis for DOPAS Plugs and Seals” (DOPAS, 2016a), describes the design basis for the FSS experiment as considered in the DOPAS Project, conceptual and basic designs, and the strategy adopted for demonstrating compliance with the design basis. The design basis is presented for both the repository reference design, i.e. the design used to underpin the safety case or licence application, and the full-scale experiment design, i.e. the design of the FSS seal components that is being tested 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, the preliminary laboratory work and its progressive upscaling, and the learning provided by the practical experience in implementing the experiment.
- D4.4, the WP4 “Integrated Report” (DOPASc 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 D4.8

This report is based on progress 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, and dismantling and rehabilitation of the surface facility was completed in December 2015. Information on all stages of the FSS experiment is included in this document.

Further details on the design and construction schedule and activities for the FSS experiment are provided in the WP3 Deliverable D3.1. In addition to summaries of the outcomes of WP2 and WP3 included in this report (D4.8), the focus is also on monitoring and performance of the concrete walls and the swelling clay core, and the learning related to the reference design. The monitoring and performance includes the monitoring of the materials in response to installation (e.g., the monitoring of the curing temperature and shrinkage of concrete following emplacement).

Scope of the FSS Experimental Work Undertaken in the DOPAS Project

As indicated above, the DOPAS Project does not cover the full extent of the work undertaken in each of the full-scale experiments. However, discussion of progress in the technical feasibility of plugs and seals (concrete walls and swelling clay cores) in this report has covered the majority of the activities undertaken in this experiment.

1.4 Terminology

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

- In this report, 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*.
- In this report, 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 plugs and seals 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.

1.5 Report Structure

This report is presented in the following sections:

- Chapter 2 provides an introduction to seals at large, describing, at a high level, the different types of seals that are expected to be constructed in Cigéo and the functions they would perform.
- Chapter 3 describes the approach that has been used within the DOPAS Project to define the design basis for the FSS experiment, and to iteratively develop a more detailed design. The discussion is captured in an overall generic process for development of the design basis for seals, referred to as the "DOPAS Design Basis Workflow".
- Chapter 4 provide summaries of the achievements of FSS with respect to the Cigéo reference seal design. These summaries are based on the design basis presented in the WP2 "Summary Report" (D2.4 DOPAS, 2016a), the assessment of the FSS design work and experiment construction presented in the WP3 D3.1 FSS Construction Summary Report (Bosgiraud *et al*., 2016) and evaluation of the performance of the experiment available at the time of report writing.

  The following is discussed:

  - Description of the reference concept, its design basis, including the safety functions performed by the seal components considered in Cigéo, the more detailed requirements addressed by monitoring of the FSS experiment, and the objectives of the associated work undertaken in the DOPAS Project (such as the WP4 related REM experiment).
  - An evaluation of the operational issues faced during the installation of the full-scale experiment components, including discussion of operational challenges

and their mitigation, and how this may affect installation of plugs and seals in Cigéo.

  - An evaluation of the performance of the full-scale experiment components, for example the extent to which the materials used meet the design basis specifications (e.g., concrete materials curing temperature and shrinkage, and emplaced bentonite materials dry density).
  - The discussion of the FSS outcomes also includes the understanding gained during the dismantling stage.
  - An evaluation of the monitoring systems used in the FSS experiment.
  - An assessment of the results of the experiment with respect to the seal components safety functions, design specifications and the objectives of the experiment, including the feedback of the results to the design basis.
  - The overall conclusions relating to the seal components (concrete walls or swelling clay core).

- Chapter 5 provides an integrated discussion of the progress achieved in the DOPAS Project on the design, construction and monitoring of FSS, at the time of writing, with respect to the seal components designs to meet the safety functions specified in disposal concepts and with respect to the technical and operational issues that have been resolved in the project.
- Chapter 6 provides a discussion of remaining technical and operational issues and how they may be addressed.
- Chapter 7 provides the conclusions from FSS, as appropriate at this stage of the Project.
- Chapter 8 provides a list of documentary references, including deliverables (DOPAS and FSS Reports, already produced or concurrently produced with this report), which are either cited in the text or otherwise of interest for an in-depth understanding of all issues. Some of these reports have a PU (Public) Dissemination status, while others are proprietary information (PP).

2 Seals in Cigéo Design

Geological disposal of radioactive waste relies on a series of complementary barriers to provide containment and isolation of the hazardous materials in the waste. The barriers include the waste form, waste primary packages and waste disposal containers, buffer and backfill materials, and the host rock, each of which will be effective over different timescales.

The depth of disposal and the characteristics of the host rock and the surrounding geological environment provide isolation from the biosphere and retardation of migrating radionuclides, and reduce the likelihood of inadvertent or unauthorised human intrusion.

As part of the backfilling of a repository, specific parts will have to be sealed. The purpose of seals will depend on the disposal concept, the nature of the geological environment and the inventory to be disposed:

- Seals may be required during operations to isolate and contain emplaced waste packages and surrounding engineered barrier system (EBS) components from the rest of the underground excavations.
- Seals may be required to limit groundwater flow and/or radionuclide migration following closure of the underground openings.
- Seals may be required to prevent inadvertent or unauthorised human access.
- In certain cases, plugs can be required for sealing investigation boreholes, in particular to intersect water producing horizons and to ensure that the boreholes do not act as a privileged radionuclide migration pathway, following repository closure.

The design basis for seals is discussed in Chapter 3. The following factors need to be taken into account when designing an underground seal:

- The purpose for which the seal is to be constructed.
- The type of excavation in which the plug is to be installed (e.g., a vertical shaft or a ramp or a horizontal opening), and the impact of the excavation on stress variations around the opening (creation of EDZ).
- The location of the plug in relation to the prevailing rock and working conditions.
- The head of water to be withstood.
- The strength of, and stresses in, the seal components.
- The shape and geometry of the seal components.
- The method of seal components construction.

The type of host rock plays an important role in defining the design requirements for seals.

High-level impacts can be recognised as summarised below, but the requirements for any particular implementation will depend on the specific nature of the host rock and the disposal concept, and will therefore be more specific and more detailed than described below.

Clay host rocks generally have low hydraulic conductivity, and can be plastic and, sometimes, soft. The plasticity and creep properties of most clay rocks (combined with re-hydration) contribute to the progressive self-sealing of any fractures (EDZ) that may develop during the construction and operation of the repository.

Underground openings in clay rocks may require lining or mechanical stabilisation during operations; this lining may need to be partly or totally removed in the seal location to ensure a tight rock interface in order to meet post-closure performance requirements.

The repository access ways represent a possible short circuit of the geosphere containment function. Therefore, the key function for seals in these systems is to close the repository such that ground water flow into, and out of, the repository is restricted by ensuring that low hydraulic conductivities are reached.

3 The Design Basis of Seals in Cigéo and Compliance of the FSS Design with the Design Basis

This chapter summarises the work undertaken under WP2 of the DOPAS Project and documented in Deliverables D2.1, D2.2, D2.3 White *et al.*, concerning the design basis of seals. It provides the context to the information presented later in the report on the evaluation of the performance of the FSS experiment with respect to the design basis of the DOPAS seals. Further details on the design basis of seals can be found in the above reports.

This chapter is structured in four sections:

- Section 3.1 discusses the meaning of "design basis", summarises the way in which design bases are developed by WMOs and presents a hierarchical structure for the design bases for plugs and seals that has been applied within the DOPAS Project. The design basis structure applied in the DOPAS Project may differ from that applied by specific programmes. Therefore, referencing of specific requirements with respect to the proposed hierarchy may differ from the manner in which the requirements are referred to in a given specific programme.
- Section 3.2 defines reference and experiment designs.
- Section 3.3 discusses compliance of designs with the design basis.
- Section 3.4 describes a generic process for preparing a design basis for plugs and seals, the DOPAS Design Basis Workflow, which was developed in DOPAS WP2.
- Section 3.5 explains the type of requirements that have been considered for experiment performance evaluation as part of this report.

3.1 The Design Basis of Plugs and Seals

In the DOPAS Project, a design basis is defined as the set of requirements and conditions taken into account in design. The design basis specifies the required performance of a repository system and its sub-systems, and the conditions under which the required performance has to be provided. It includes requirements derived from regulations, and safety functions that plugs and seals have to fulfil as part of the overall safety objective of a disposal system. Requirements are statements on what the design has to do (i.e., the performance) and what it must be like (i.e., the characteristics). For a plug/seal, this could be, for example, the strength / the hydraulic conductivity of the materials making up the plug/seal. Conditions are the loads and constraints imposed on the design, for example, the underground environment (dimensions, air temperature, humidity, etc.) or controls on the manner in which the design is implemented (e.g., the time available for construction).

The requirements in the design basis form a hierarchy of increasing detail, which is developed in parallel with decisions on the design. At each stage in the design development process, the requirements are used as the basis for more detailed designs. Therefore, although there is a transition from problem specifications to solutions during design development, requirements are defined at each stage in the process as the basis upon which more detailed designs are developed. For example, development of a disposal system conceptual design requires description of the sub-systems that make up the conceptual design at the same time as developing the statements regarding the functions that these sub-systems must provide. At a more detailed level of design development, designing a specific plug/seal component (e.g., defining a concrete mix for a plug/containment wall) requires information on what the concrete mix must achieve (e.g., strength, curing temperatures, and shrinkage), but also leads to detailed design specifications (e.g., the acceptable range of constituents that can be used when mixing the concrete). These design specifications can be transferred into quality control statements and construction procedures for implementation during repository operations.

The processes used by WMOs to develop requirements and conditions that form part of the design basis, are expressed in different ways using different terminologies. However, these processes are largely comparable to each other. Some commonalities that have been identified include:

- Using the experience gained from previous tests and experiments on plugs and seals and/or from underground mining activities.
- Using an iterative process involving the design basis, performance assessment and safety evaluation to fine tune the design basis for the final plug/seal system, paying due consideration to the constructability and durability of these complex structures. This shows that requirements may be subject to change as the design process evolves. The principal safety functions of a plug or seal component can be formally specified and stabilised once the repository concept has been established and the national regulations developed. More detailed requirements are developed through an iterative process in parallel with specific design activities, including materials research and full-scale testing. There is a need to identify and describe change management processes to respond to design basis revisions to operate alongside these processes.
- Performing critical design reviews periodically to assess the results, to check the compliance of designs with the design basis, and to identify possible modifications to the design basis.

All of the work undertaken to develop the design basis needs to be reflected in the safety case, and integrated with work undertaken on development and management of the safety case.

Some WMOs use hierarchies to describe and present the design basis. Furthermore, a structured design basis can link safety functions to design specifications, and, if the design specifications are written appropriately, these can form the basis of construction and quality control procedures.

Building on this context, in the DOPAS Project, the requirements contained in the design basis of seals are described in terms of the following hierarchy:

1. *Stakeholder requirements*: Stakeholder requirements are the top-level statements on, and description of, what must be achieved by a waste management programme and elaboration of specific approaches that must be considered in the repository design.

2. *System requirements*: The requirements on the disposal system, i.e., the safety functions provided by the elements that comprise the disposal system. For plugs and seals, therefore, system requirements are the safety functions provided by plugs/seals.
3. *Sub-system requirements*: A list of the functions that the components that comprise the plug/seal must provide and the qualities that these components must have.
4. *Design requirements*: Qualitative statements describing the qualities or performance objectives for plug/seal components.
5. *Design specifications*: A list of quantitative statements describing the plug/seal components (e.g., how they should be emplaced, the dimensions of the components, the materials to be used and the acceptable tolerances), prepared as a basis for development of the detailed design.

Following the definition of the design basis presented above (the design basis is the "set of requirements and conditions taken into account in design"), the argument that the design basis is developed in parallel with decisions on the design, and that at each stage in the design development process requirements are used as the basis for more detailed designs, it is appropriate for all of the statements contained at all levels of the hierarchy to be referred to as "requirements", with clarification added by use of the more specific term.

3.2 Cigéo Reference and FSS Experiment Designs

In the DOPAS Project, a distinction has been made between reference and experiment designs:

- The term "reference design" is used to denote the design of a seal within a disposal concept, i.e., the design used to underpin the safety case or licence application (Cigéo in our case).
- The term "experiment design" is used to indicate the design of the seal being tested, e.g. the design of FSS in DOPAS.

The FSS experiment design is a modified version of the Cigéo reference design, with the modifications made to investigate some specific aspects of the design during the experiment. In particular, there are differences in the boundary conditions between the experiment design and reference design. These include the number (and size) of seals in Cigéo (just one seal for the FSS experiment compared to many tens of seals for the repository) and the impact on the construction of these seals (for example cost constraints), and the acceptability, for an experiment, to use monitoring instrumentation within the experimental (FSS) seal structure which will not be accepted in the real (Cigéo) seal. Other differences generally arise as a result of experiment-specific objectives, for example to test alternative designs and compare the performance with the reference designs (e.g., FSS is a test of 2 types of low pH concretes: shotcrete and SCC, while Cigéo will do with one type only for containment walls).

During the initial stages of design development, experimental designs are, by necessity, more detailed than the reference designs that they are testing. For example, reference designs may only be developed to the conceptual level. The testing of the conceptual design at the detailed level in a full-scale experiment allows requirements to be clarified and to establish feasibility for one or other design solution. Testing of this sort is sometimes referred to as *concurrent engineering*, i.e. the development of a design at multiple levels of detail at the same time. The results of testing an experimental design will lead to an updated reference design basis.

3.3 Compliance

The strategies and approaches used by WMOs to demonstrate compliance of the reference designs of plugs and seals to the design basis include among other things:

- Full-scale Testing: Full-scale testing is the main strategy adopted by WMOs (including Andra, and as requested by the Nuclear Authority) to compliance demonstration of plugs and seals. Full-scale experiments include demonstration of technical feasibility, tests of performance, and combined technical feasibility and performance tests.
- Construction Procedures: WMOs have different approaches to describing the use of construction procedures for compliance demonstration. Some describe construction procedures as an important element of compliance demonstrations, and others consider it to be part of quality control during repository implementation. In any case, the focus of quality control/assurance relies to a large extent on the practical experiences gained during "compliance demonstration".
- Monitoring: WMOs have different approaches to the use of monitoring as part of compliance demonstration strategies for plugs and seals. Some WMOs have not made firm decisions on how to monitor repository plugs and seals (e.g., Andra), while others are considering monitoring of repository plugs and seals (e.g., through instrumentation in demonstrators or indirectly) to provide for compliance demonstration (e.g., Posiva).

Compliance of designs with the design basis is discussed further throughout this report with respect to the evaluation of the performance of the FSS experiment with respect to the reference design basis of Cigéo.

3.4 The DOPAS Design Basis Workflow

Work on the design basis in the DOPAS Project has allowed consideration of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis of plugs and seals. The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. The learning provided by WP2 has been used to describe a generic process for development of the design basis for plugs and seals called the "DOPAS Design Basis Workflow" (Figure 3.1). This workflow is structured to be consistent with a hierarchy of increasingly detailed designs (IAEA, 2001), as follows:

- Conceptual Design: Conceptual designs describe the general layout of a repository structure, including the different repository components and how they are arranged, and the type of material used for each component (e.g., concrete, bentonite, gravel). In a conceptual design, the environmental conditions (including rock characteristics) are presented in generic terms, for example by describing the nature of the processes occurring rather than quantifying the processes. The performance of the components and the overall structure are described qualitatively.

- Basic Design: In a basic design, the components in the conceptual design are described in more detail with an approximate quantitative specification of geometry and material parameters. The properties of the environmental conditions are presented in detail, which requires characterisation of the site or elaboration of the assumptions underpinning the design. Performance is described quantitatively.
- Detailed Design: In a detailed design, the concept is presented in such detail that it can be constructed, i.e., it provides precise information on all aspects of the seal components.

At the conceptual design stage, the design basis for a plug/seal includes the stakeholders' requirements that define the overall objectives of geological disposal (e.g., the safety criteria that must be met), safety functions for each of the components of the disposal system (e.g., for plugs and seals, this may include limiting groundwater flux through the repository), and the sub-system requirements on each of the components of a plug/seal (e.g., the role of a concrete wall and the wall lifetime). The safety functions are dependent on decisions made on the safety concept, and sub-system requirements are dependent on conceptual design options. Consideration of the site environmental conditions and loads acting on the structures allows conduct of a performance assessment, the results of which feed into a compliance assessment used to ascertain whether the system and sub-system requirements have been met by different conceptual design options. The outcome is selection of a conceptual design of a plug/seal, and elaboration of preliminary design requirements to be tested during development of the basic design.

At the basic design stage, preliminary design requirements are used as the basis for developing preliminary basic designs. During the DOPAS Project, basic designs have been tested through full-scale tests, including FSS. This has required the development of experiment design specifications (contained in a tender document), which are used to design the experiment and as the basis for performance evaluation. These design specifications represent working assumptions for reference design specifications, which might be adopted as reference design specifications following evaluation of experiment performance. The full-scale demonstration experiments undertaken in the DOPAS Project have addressed specific objectives, for example, technological feasibility (FSS), performance (DOMPLU), alternative design options (POPLU), and materials research in support of preliminary basic design (EPSP and ELSA).

The results of full-scale tests (of FSS) provide further support to design decisions, especially optimisation issues such as the identification of design solutions that represent the most appropriate technique and the most appropriate performance.

The DOPAS Design Basis Workflow is based on the design basis work undertaken for plugs and seals within the DOPAS Project. However, the "Workflow" is generic in nature, and could be applied to other repository design activities.

The general applicability of the DOPAS Design Basis Workflow is considered as part of the wider DOPAS Project dissemination activities (WP7).

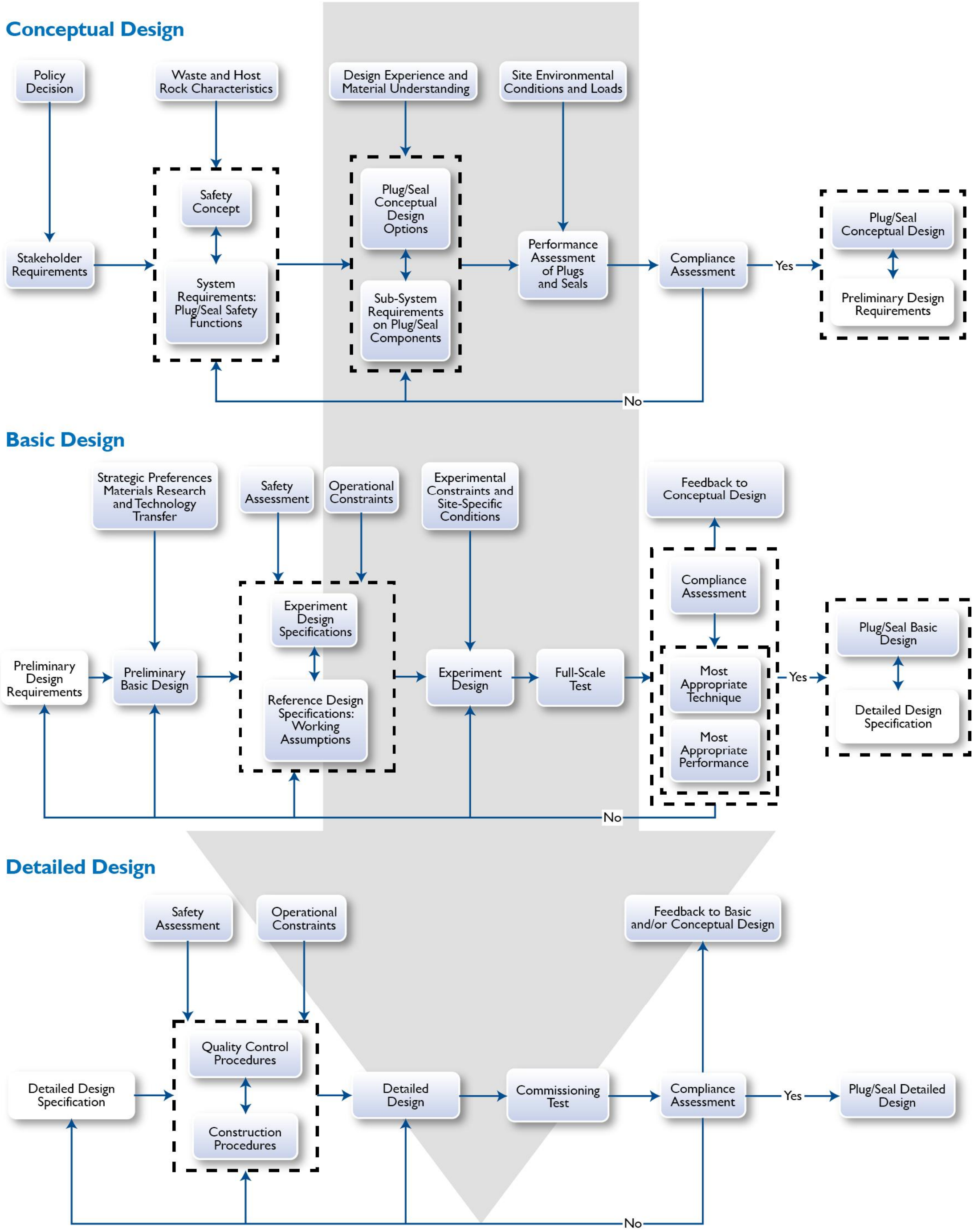

Figure 3.1: The DOPAS Design Basis Workflow. Dashed boxes are used to show activities undertaken in parallel.

3.5 Consideration of the Cigéo Design Basis in the FSS Experiment Performance Evaluation

In the next chapters, the performance of the FSS experiments conducted in the DOPAS Project is presented and compared to the Cigéo design basis as developed in WP2. In order to undertake this evaluation, a sub-set of the design basis requirements has been considered:

- The safety functions (system requirements) for the seal components are evaluated.
- "Key" design specifications that were addressed through design work (materials development and testing, including associated numerical modelling), experiment construction (including associated quality control) are evaluated. The list of key design specifications has been selected based on expert judgement of the FSS experiment leader (Régis Foin) and Andra's colleagues to represent some of the principal design specifications that need to be considered in seal components performance, but do not include all design specifications. Further analysis of experiment performance by Andra will consider the full range of design specifications collated in the design basis.

4 Andra's Drift and ILW Vault Seal

This chapter discusses the FSS achievements within the DOPAS Project, in particular the design, construction and dismantling of the FSS experiment, with respect to Andra's reference drift and ILW vault seal:

- In Section 4.1, the design basis for the drift and ILW vault seal is described, focusing on the safety functions assigned to the seal, a summary of the reference design, and presentation of the key design specifications contained within the design basis and which are directly tested through measurement and monitoring of the FSS experiment. More information on the design basis can be found in WP2 Deliverables, White *et al*. (2014).
- In Section 4.2, the FSS experiment is described, including the objectives of the experiment, and a summary of the design work, construction of the test box and installation of the FSS components. More details on the construction of the FSS experiment are in WP3 Deliverable D3.1 FSS Construction Summary Bosgiraud *et al*. (2016).
- Section 4.3 discusses the learning from the FSS experiment with respect to the operational issues that will be faced during installation of Andra's reference drift and ILW vault seal at time of Cigéo closure operations.
- In Section 4.4, the performance of the FSS components is evaluated, and conclusions drawn regarding the suitability of the materials and the emplacement methods used to install the materials for application in the repository.
- Section 4.5 evaluates the results achieved from the dismantling of FSS.
- Section 4.6 evaluates the performance of the measurement system used in the FSS experiment and its applicability in repository monitoring.
- Section 4.7 presents evaluation of the compliance of the FSS experiment with the design basis, the feedback of the results to the design basis and discusses the learning outcomes from the work.
- Section 4.8 presents the overall conclusions from the FSS experiment relating to Andra's reference drift and ILW vault seal.

As discussed before, 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 (amongst other Deliverables) in the WP5 D5.10 Summary report (Rübel *et al*., 2016) and referenced therein.

4.1 Design Basis for Andra's Drift and ILW Vault Seal

4.1.1 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.

4.1.2 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 4.1).

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.

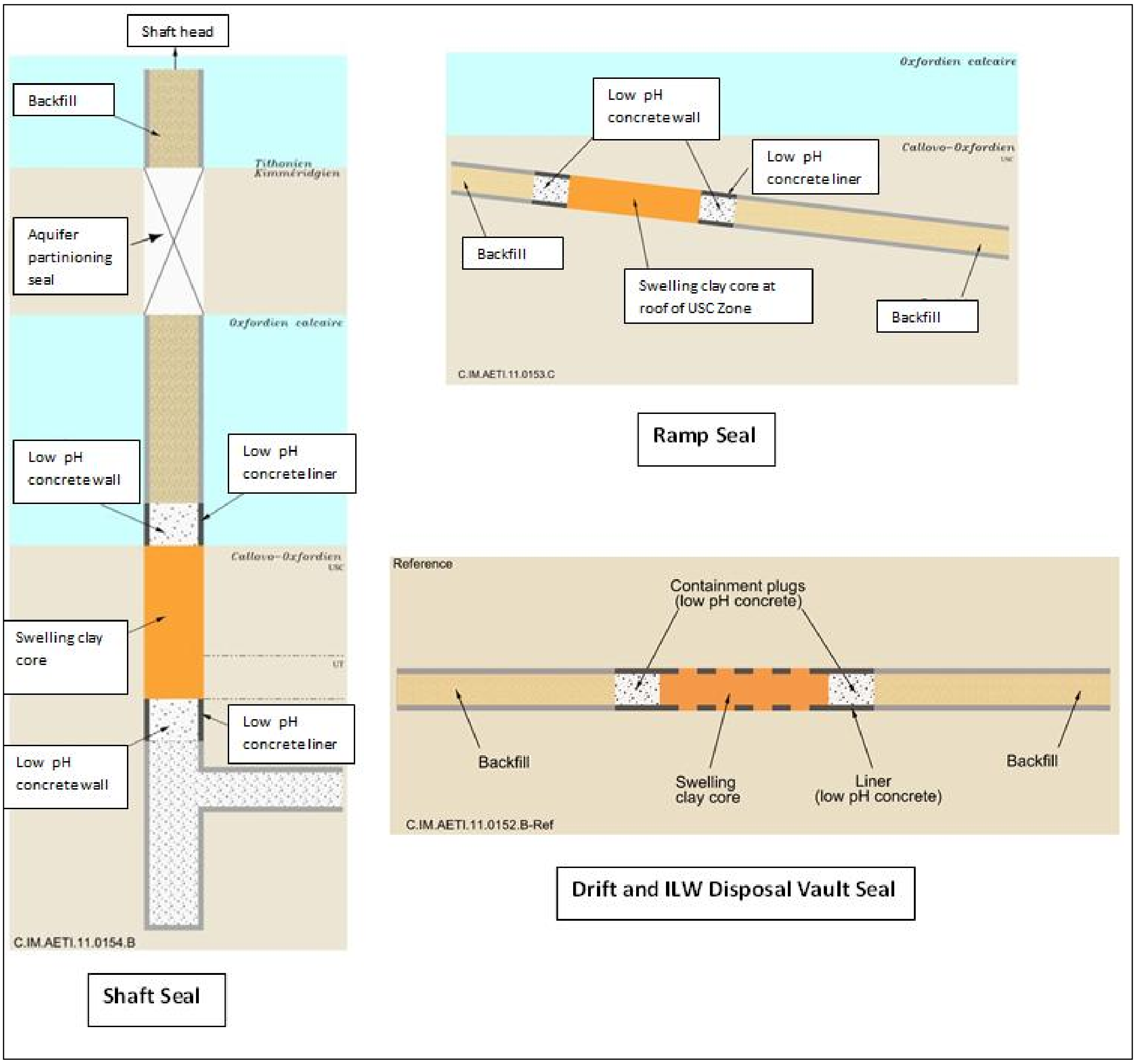

Figure 4.1: Schematic illustration of the conceptual designs for shaft, ramp, and drift and ILW disposal vault seals for the Cigéo reference disposal concept (Andra).

4.1.3 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 4.1. More information on the design basis can be found in WP2 Deliverables, 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 summary report. Evaluation of the performance of the FSS experiment compared to the design basis is an on-going activity within Andra (e.g., pH evolution with time for low pH concretes, SCC or shotcrete).

Table 4.1: Key design specifications tested through measurement of the results of the FSS experiment or during materials development as part of the experiment.

ID	Design Specification	Justification	Compliance Approach
FSSDS01	The pH of the concrete shall not exceed a value of 11, and shall ideally lie between 10.5 and 11 at 28 days.	At pH < 11, the impact of cement leachate on bentonite and argillite performance is acceptable.	Three recipes were tested in the laboratory (B50 CEM III/A; B50 CEM I; and B40 CEM III/A).
FSSDS02	The maximum curing temperature of the concrete 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. The 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 the SCC and shotcrete containment walls.
FSSDS03	The strain as a result of shrinkage of the concrete shall be less than 350 µm/m at 90 days.	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 core and withstand a swelling pressure of up to 7 MPa. 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. A temperature gradient that would result in cracking has not yet been defined in Andra's programme. Therefore, the requirement has been defined in terms of strain. A strain of 350 µm/m has been specified by reference to more traditional values (500 µm/m) that are commonly found in civil engineering.	Monitoring of strain (shrinkage) in the concrete walls.
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.

ID	Design Specification	Justification	Compliance Approach
FSSDS05	The low-pH SCC shall have a characteristic compressive strength of at least 30 MPa at 28 days and 40 MPa at 90 days.	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 days.	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 DOPAS. (2016a).	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.

4.2 Summary of FSS Experiment

4.2.1 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 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 4.2.

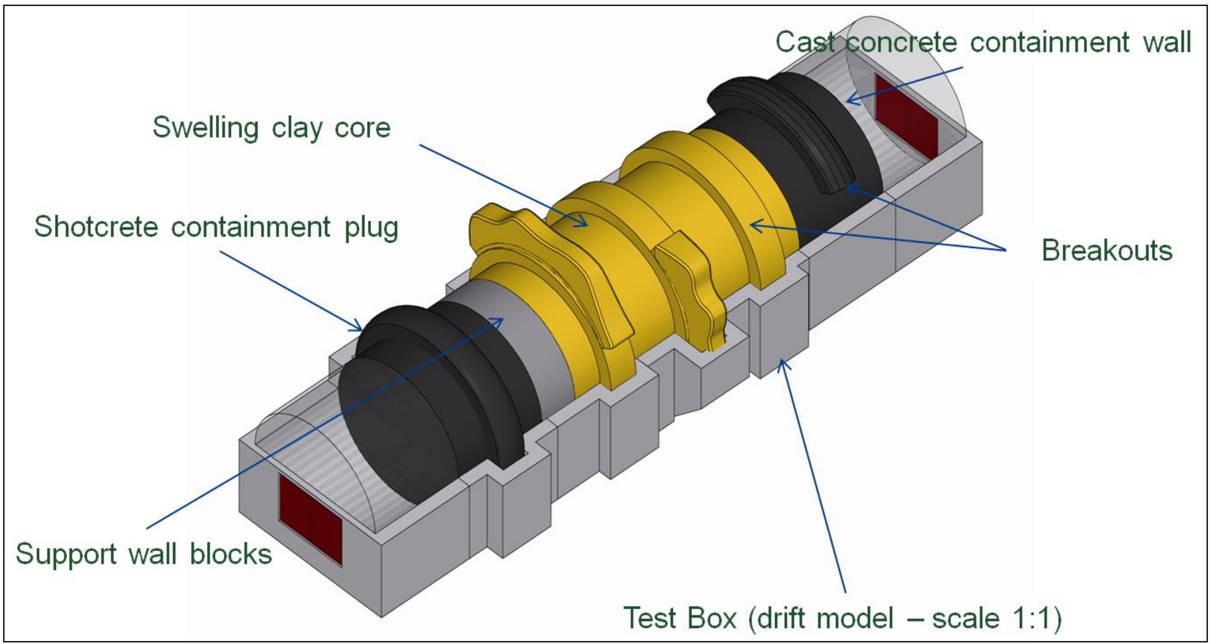

Figure 4.2: Schematic illustration of the FSS experiment design.

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 WP2 Deliverables, DOPAS (2016a).

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.

4.2.2 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 components.

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

Materials Development and Testing:

Selection of the low-pH SCC mix was based on a series of laboratory and metric-scale tests in which eight binder options were down-selected, based on measurement of properties and performance in the metric-scale tests. Properties measured included pore solution pH, compressive strength, curing temperature and porosity. Observations during metric-scale tests included distribution of aggregates, aggregate/paste separation and bleed water. The final selection of the preferred mix was based on a global analysis of pH, shrinkage, manufacturer location, workability, presence of organic matter and cost. The mix selected was B50 CEM III/A 52.5 Rombas, which is a mix containing 50% cement and 50% silica fume.

Three candidate mixes for the low-pH shotcrete were subjected to laboratory tests and to spraying of metric test panels. The panels were tested for compressive strength, pH, porosity, workability and shrinkage, and the observed rebound was recorded. The selection of the preferred shotcrete mix was also based on a global analysis, which considered the same parameters as for the global analysis of the low-pH SCC, plus the odour of the mixture resulting from sulphur present in the slag materials and the compressive strength. The mix selected was "B50 CEM I 52.5 Le Teil", which is mix containing 20% cement, 32.5% silica fume and 47.5% slag.

For the swelling clay core, Andra selected a pellet-based system instead of pre-compacted bentonite blocks because this solution is considered by Andra to be a more efficient industrial method of implementation at a scale such as that encountered in Cigéo. Andra specified the use of a pure sodium bentonite, without any other constraints, for the swelling clay core. The contractor chose WH2 bentonite (a product similar to the MX80 brand) from Wyoming. The initial requirements on the swelling clay materials focused on the swelling pressure and hydraulic conductivity; these are 7 MPa and 1×10^{-11} m/s, respectively (see Table 4.1). During material testing, the dry density value of 1620 kg/m^3, corresponding to a swelling pressure of 7 MPa after hydration, was initially specified to ensure that the required swelling pressure could be achieved. In practice, the density required to achieve a hydraulic conductivity of 1×10^{-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.

The bentonite was emplaced as an admixture of 32-mm diameter pellets and powder to meet the density requirements. Laboratory testing demonstrated that this was best achieved through use of crushed pellets rather than standard WH2 powder (the crushed pellets are thereafter referred to as “powder”). Mock-up testing (at a metric scale) used as part of the emplacement machine design process further demonstrated that the admixture was most efficiently emplaced when using screw augers with the auger supplying the pellets positioned beneath the auger supplying the powder. In parallel with the mock-up tests, further investigation into the required swelling pressure concluded that a pressure of 5 MPa would be sufficient to meet the safety functions of the seal. In parallel to the FSS experiment implementation, a proper dimensioning of the containment walls was carried out by Andra (within the frame of the more general Cigéo design studies), showing a significant impact of the swelling pressure on the containment wall size. Subsequently, the 5 MPa value was also chosen as a reasonable compromise between the containment wall geometry and long-term performance. This revised requirement could be met with an emplaced dry density of the bentonite materials in the swelling clay core of 1500 kg/m^3.

Siting and Construction of FSS

FSS was constructed in a surface warehouse as it provided the most suitable solution with respect to logistical limitations of conducting the experiment underground at the Bure URL. It was most favourable in terms of other activities already planned at Bure, and it was favoured in terms of experimental costs, schedule and needs for dismantling.

The FSS test box (or drift model) design concept was specified by Andra to contain the FSS experiment. The test box was constructed of standard Ordinary Portland Concrete (OPC) using standard construction techniques and was keyed into the facility floor for structural stability. The test box was fitted out with a local “mine-like” exhaust ventilation system, with a closing door in the front of the box, in order to control the ambient temperature (18°C < q < 30°C) and humidity (50% < HR < 75%) inside the box, consistent with a requirement on the experiment specification to simulate actual *in situ* conditions. It was also equipped with some polycarbonate observation windows at its periphery to visually evaluate the backfill quality.

Installation of seal components started with the construction of the first concrete containment wall inside the test box (low-pH SCC), followed by bentonite clay core emplacement in parallel with a support wall made of low pH prefabricated concrete bricks. The last installed component of FSS was the second containment wall, made of low-pH shotcrete. The installation of the measurement system was undertaken in parallel with installation of the other components.

Further details on the design and construction of FSS are provided in the WP3 Summary Report (DOPAS 2016b) and in WP3 Deliverable D3.1 (Bosgiraud *et al*., 2016) and the references contained therein.

4.3 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 D3.30 DOPAS (2016b). 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 (heat dissipation in the host rock will probably be less efficient than inside the 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).

4.4 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 4.1 is evaluated:

- Section 4.4.1 discusses the performance of the SCC and shotcrete containment walls with respect to the curing temperature (FSSDS02) and strain (FSSDS03) design specifications.
- Section 4.4.2 discusses the performance of the bentonite swelling clay core with respect to the bentonite density design specification (FSSDS07).

The systems used to measure and monitor the installation of FSS are described in WP4 Deliverable D4.1 (Noiret *et al*, 2016) and are illustrated in Figure 4.3 and Figure 4.4.

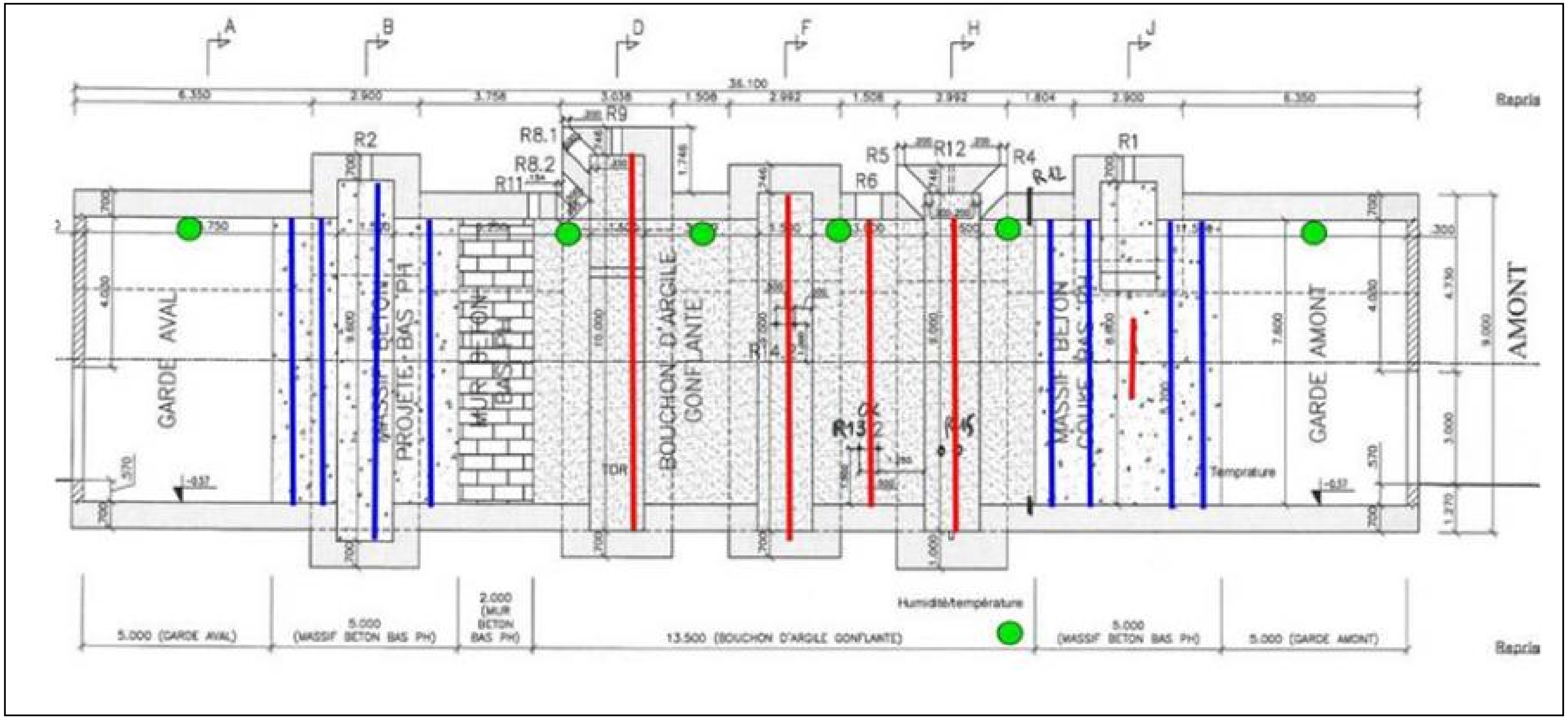

Figure 4.3: Location of the different sensors in FSS (**blue**: strain and temperature sensors in the low-pH concrete containment walls; **green**: relative humidity and temperature sensors; **red**: TDR sensors located in the swelling clay core).

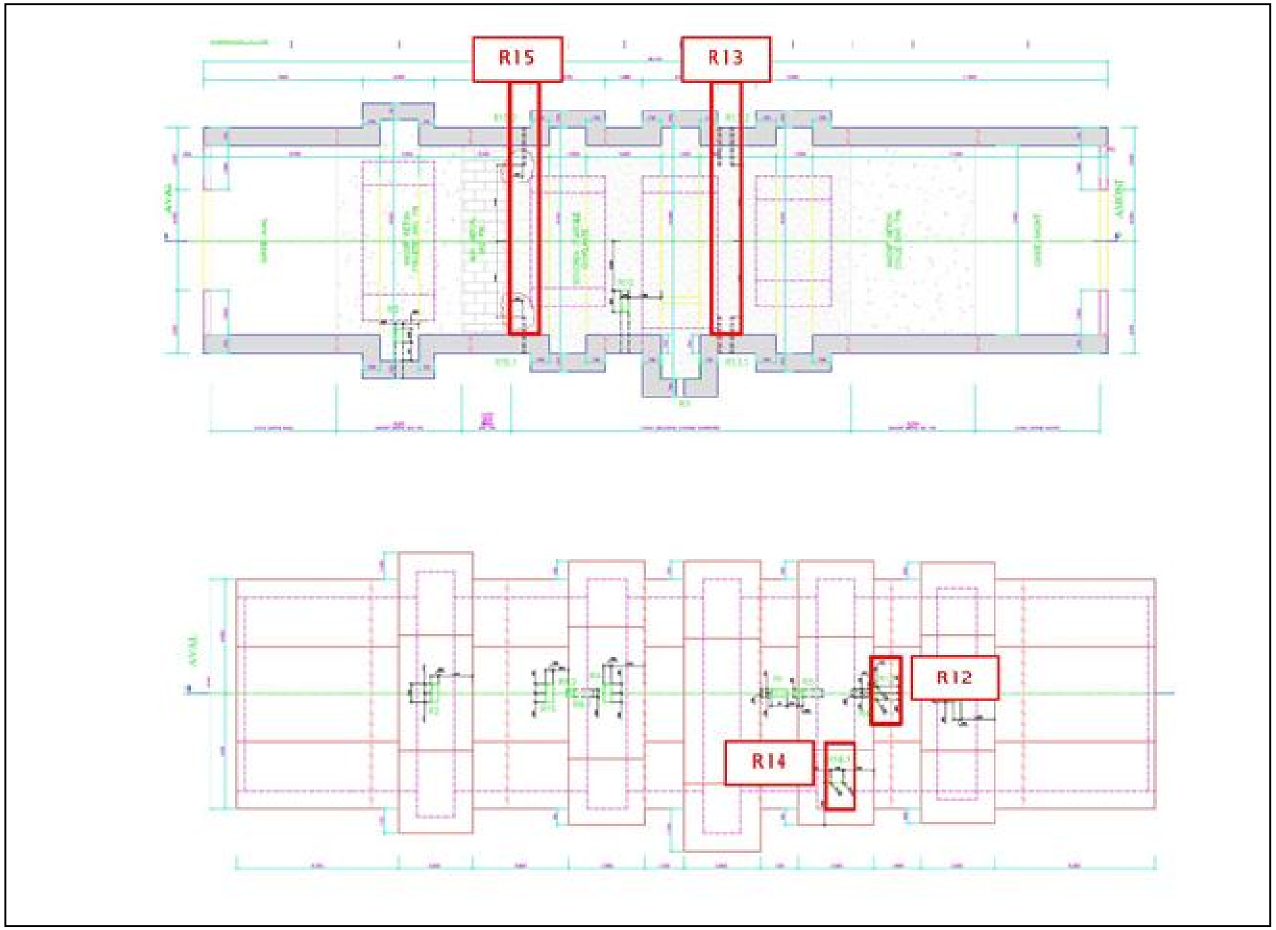

Figure 4.4: Location (**in red**) of the different pipes pre-positioned in FSS for gamma-gamma logging of the swelling clay core.

4.4.1 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 4.3). To measure the strain, 18 strain gauge sensors in three sections for each type of containment wall were oriented in the vertical (Figure 4.3) 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 4.3) for the SCC containment wall and Section 5 (first blue section after the red sections on the left-hand side of Figure 4.3) for the shotcrete containment wall are shown in Figure 4.**5** and Figure 4.6, respectively. Measurements at other locations for each containment wall are summarised in Table 4.2 (SCC wall) and Table 4.3 (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).

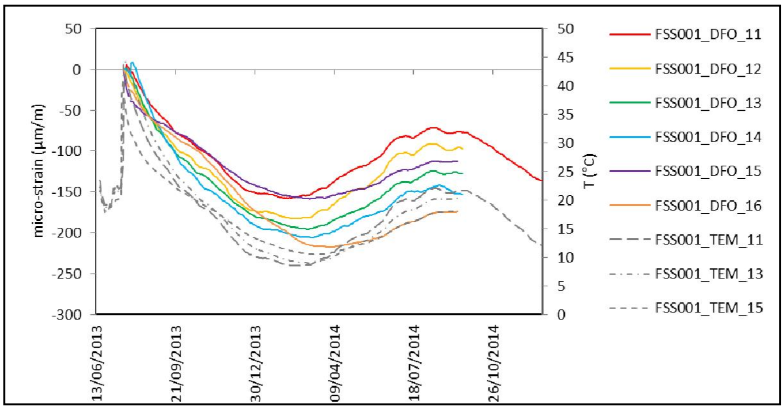

Figure 4.5: Temperature and strain measured for the low-pH SCC containment wall at the Section 1 location.

Table 4.2: 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

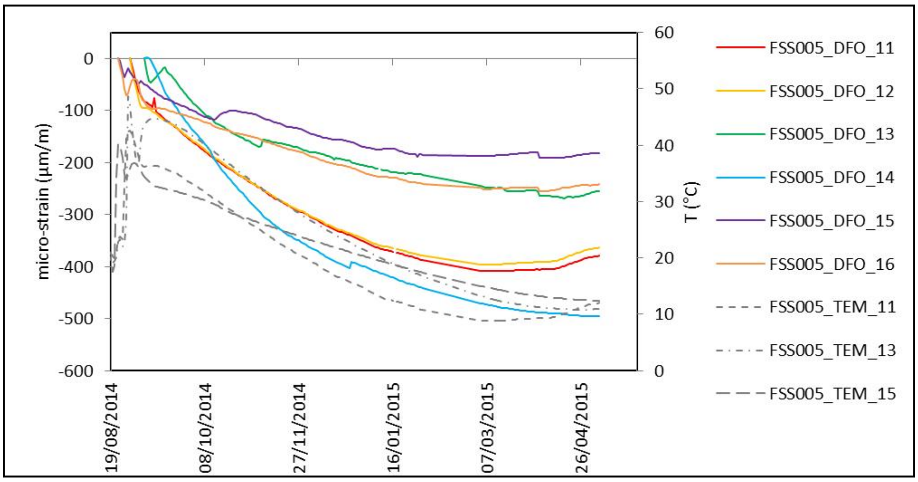

Figure 4.6: Temperature and strain measured for the low-pH shotcrete containment wall at the Section 5 location.

Table 4.3: 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

4.4.2 Bentonite Swelling Clay Core: Compliance with FSSDS07

In order to compare the emplaced bentonite dry density with the 1620 kg/m^3 design specification and the new specification (1500 kg/m^3) determined at the end of the metric emplacement tests, the density was measured using 3 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.
- TDR penetrometer measurements along the profiles shown in Figure 4.3 and further described below.
- Gamma-gamma logs along the profiles shown in Figure 4.4.

In order to provide a comparison with the dry density design specification, the results from the 3 methods were combined as described below.

Mass Balance Estimation of Bentonite Dry Density

The mass balance estimation was carried out as follows:

- 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).
- 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).
- For the bentonite materials, each big bag (of pellets) and each octabin (containing the powder) was tagged and weighed before use.

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. 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:

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

The positioning of the TDR sensors inside the test box (periphery) is illustrated in Figure 4.7, while Figure 4.8 shows the effective TDR sensors emplacement inside the FSS test box prior to bentonite mix backfill operations.

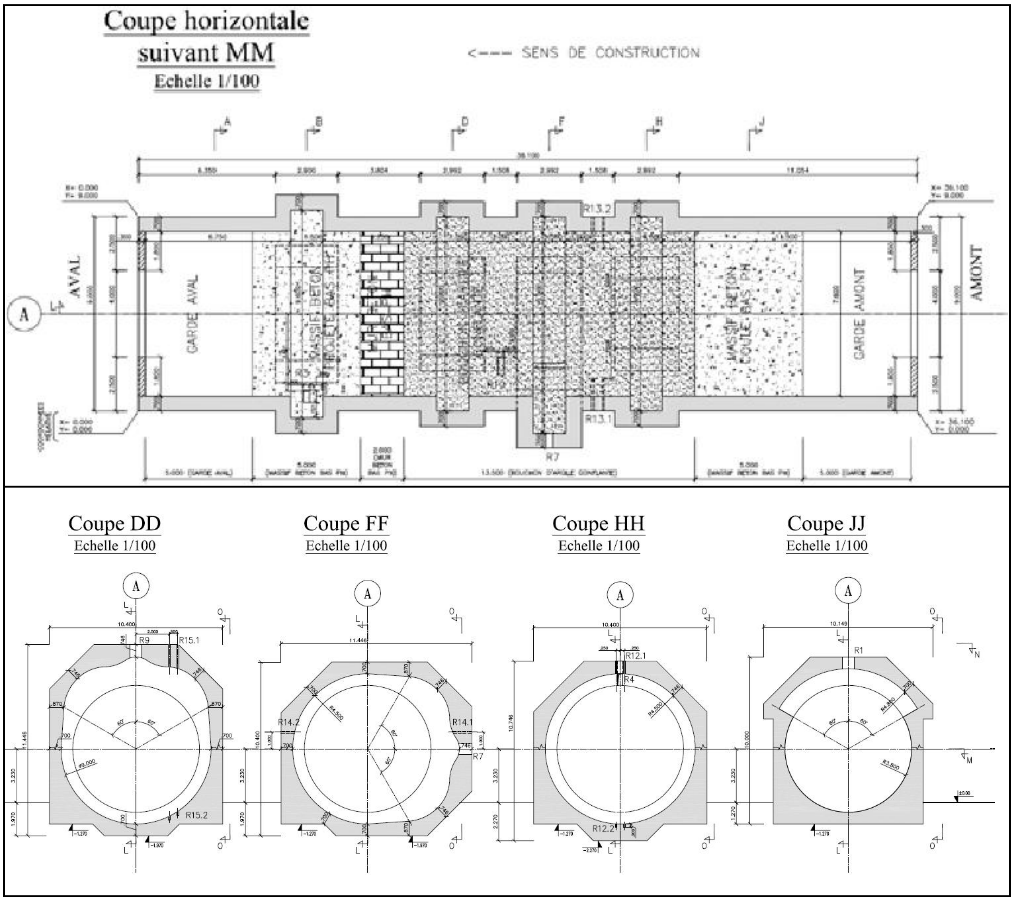

Figure 4.7: Longitudinal (top) and sectional (bottom) positioning of the TDR sensors.

Figure 4.8: 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 4.9 shows the TDR sensors emplaced inside the metric concrete pipe used for this purpose.

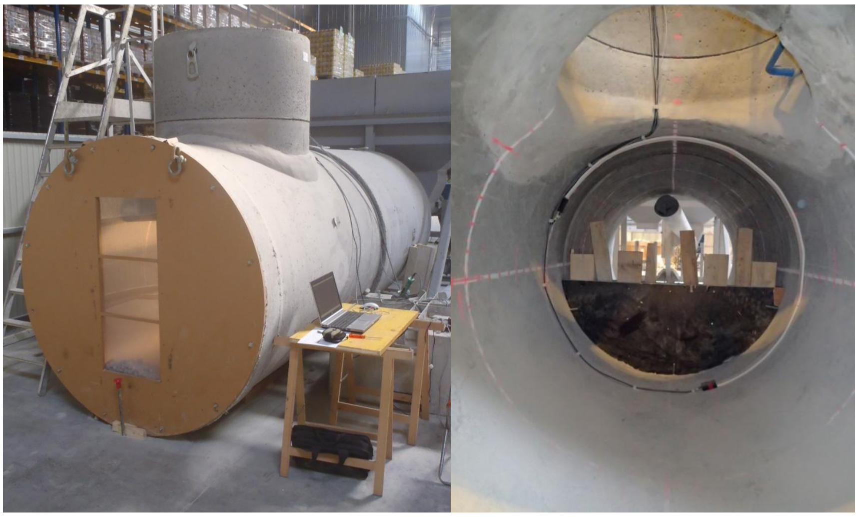

Figure 4.9: TDR sensor calibration inside the metric emplacement test pipe.

The results obtained on sections HH, FF, DD and JJ (see Figure 4.7) are illustrated by images, an example of which is shown in Figure 4.10 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 4.4.

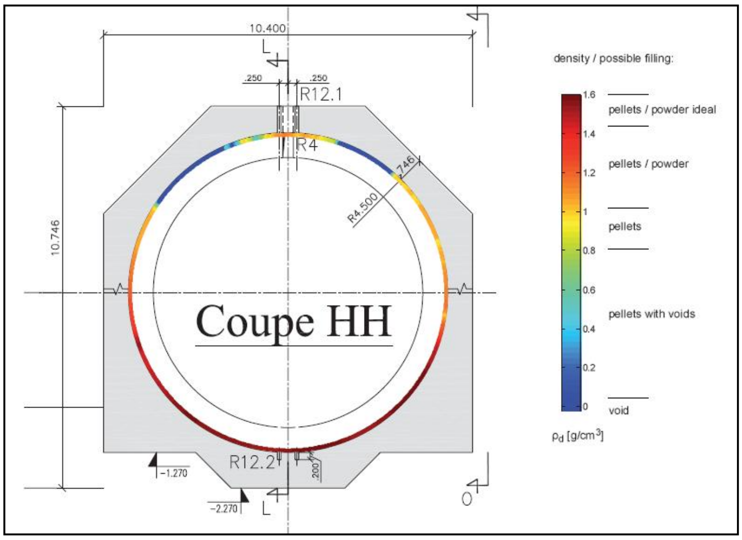

Figure 4.10: Illustration of TDR sensors measure of dry mix density at the HH section.

Table 4.4: 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 4.11).

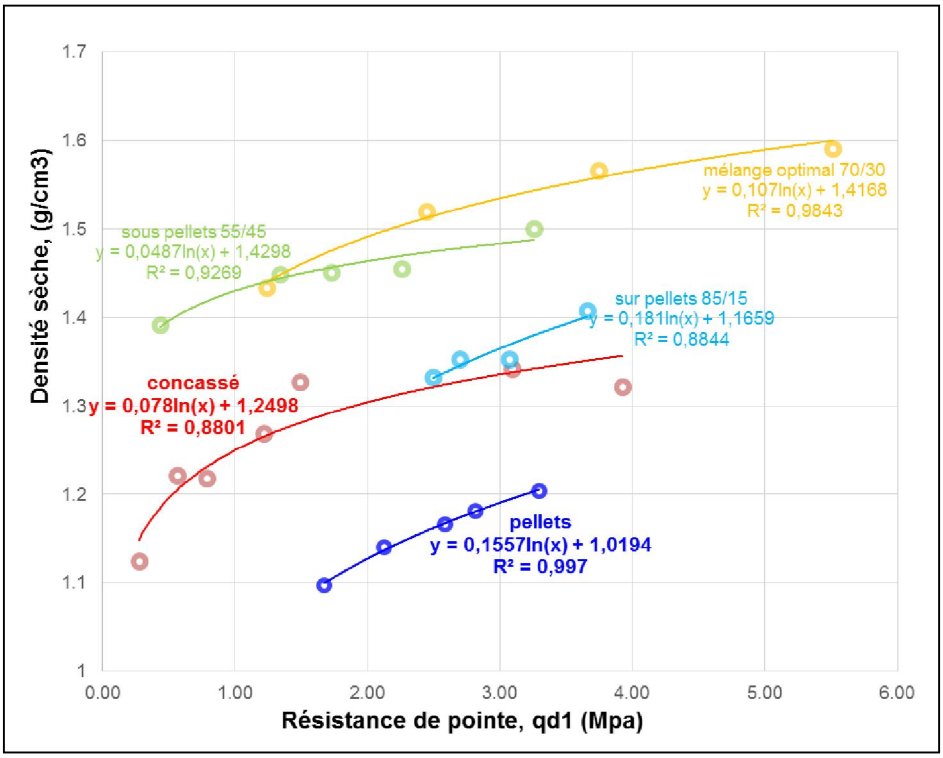

Figure 4.11: Calibration curves for the five bentonite mixes tested. “Densité sèche” means “dry density”, “mélange” means “mix”, “concassé” means “crushed”, and “Résistance de pointe” means “resistance of the tip” of the penetrometer.

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 practical "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 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 which were the only "fully operational tool" adapted to measure the spatial variability of the bentonite dry density (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 even if this method is unlikely to be employed in Cigéo.

Practically, the most adapted 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.

4.5 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 (more detailed information is available in Deliverable D4.1 Noiret *et al.* (2016)).

- Section 4.5.1 describes the survey and the nature of cracks as observed at the surface of the sawn sections in the two containment walls;
- Section 4.5.2 discusses the quality of concrete.

The dismantling activities of the FSS experiment, which took place between August 2015 and December 2015, are illustrated in Figure 4.12.

(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 4.12: 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 4.12 (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, as shown in

Figure 4.**13**, before demolition using a digger. (Figure 4.12 (c) and (d)).

During the dismantling, the bentonite core material was removed and placed in bags for recycling (Figure 4.12 (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.

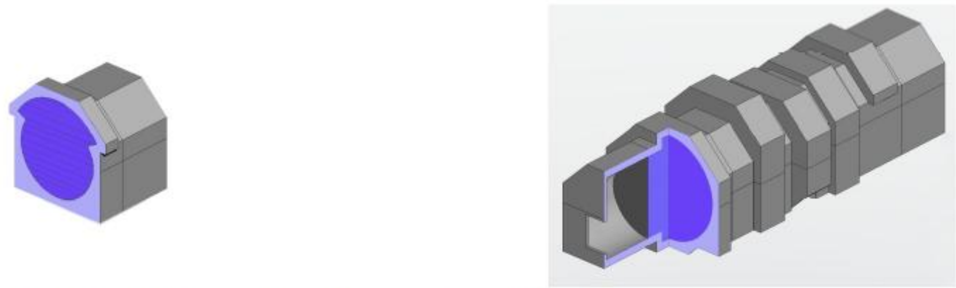

Figure 4.13: Sawing of the SCC containment wall (transversally, left) and the shotcrete containment wall (transversally and longitudinally, right) in the "clever" dismantling activities of FSS.

4.5.1 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 4.14 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 D3.30 DOPAS (2016b), 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 means 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.

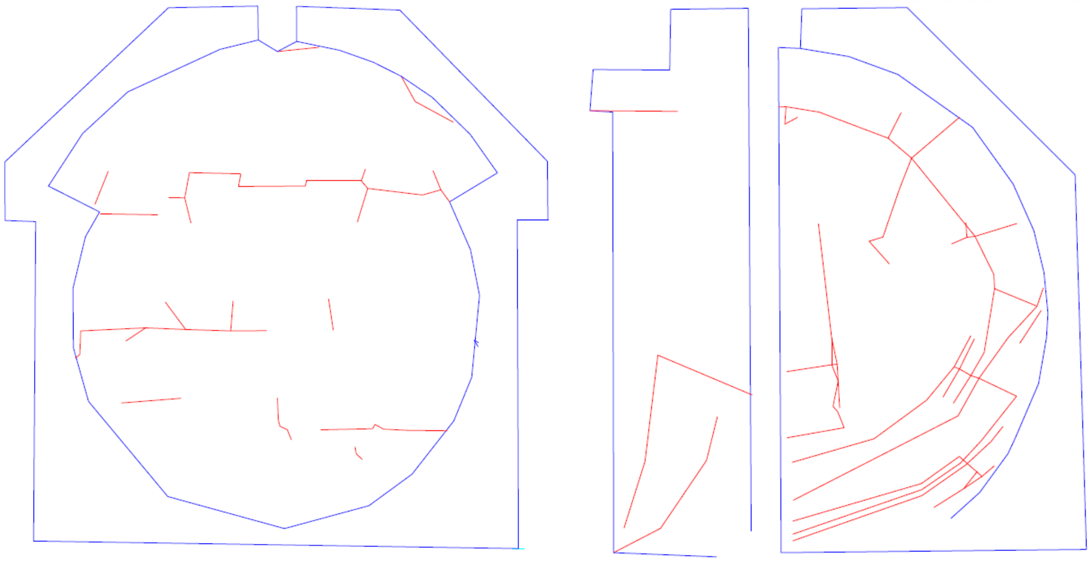

Figure 4.14: The pattern of cracks in the low-pH SCC (left) and shotcrete (right) containment walls.

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).

4.5.2 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 4.15 presents the results for the strength (in MPa) of the concrete and shotcrete containment walls.

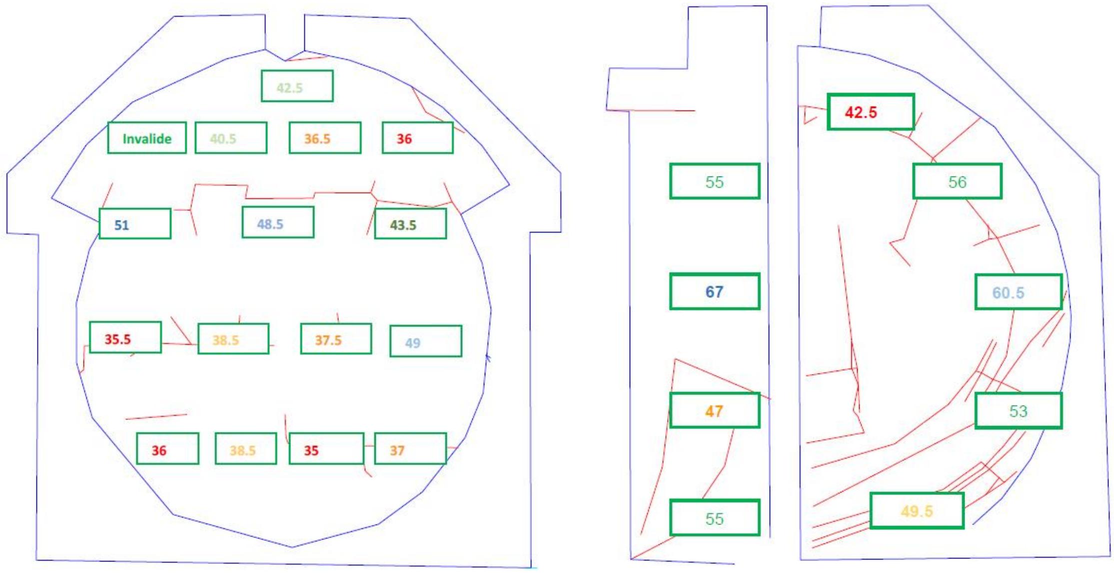

Figure 4.15: Results for hardness tests on the concrete (left) and shotcrete (right) containment walls (numbers indicate values in MPa).

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.

4.6 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.

4.6.1 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.

4.6.2 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.
- 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.

Table 4.5: 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.

4.7 Assessment of Compliance with the Design Basis and Overall Conclusions from FSS related to Andra's Reference Drift and ILW Vault Seal

In this section, the results from FSS are discussed with reference to:

- Compliance with the safety functions presented in Section 4.1.1.
- Compliance with the design specifications listed in Table 4.1 of Section 4.1.3, and with respect to general learning obtained during the experiment.

4.7.1 Compliance with the Drift/ILW Vault Seal Safety Functions

The safety functions of the drift and ILW vault seals are qualitatively specified as follows:

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

Practically, the capacity to emplace a 1500 kg/m^3 dry density swelling clay core at full scale is proven. The density achieved is compliant with the expected hydraulic performance of the seal. The capacity to emplace a large low pH SCC containment wall with homogeneous physical and chemical properties is also demonstrated. Thus, this type of material is deemed well adapted to sustain the forces induced by the bentonite swelling phenomenon at the time of resaturation. The proven feasibility of constructing the seal to the required standards in FSS demonstrates that the seal in Cigéo will be expected to provide its required safety functions.

The results from complementary experiments, including the REM experiment (cf. Deliverable D4.2 Conil *et al*.) will need to be taken into account in order to demonstrate full compliance with the safety functions.

The compliance of FSS with the safety functions is also met by linking the safety functions to more detailed requirements (design specifications). Evaluation of the performance of the FSS experiment with respect to the design specifications is described further.

4.7.2 Compliance with Design Specifications and General Learning from FSS

An evaluation of the compliance of the FSS experiment with the design specifications listed in Table 4.1 is presented in Table 4.6.

The implications are discussed below.

Table 4.6: Compliance assessment for key design specifications on the FSS experiment.

ID	Requirement / Design Specification	Compliance Assessment	Feedback to Design Basis
FSSDS01	The pH of the concrete shall not exceed a value of 11, and shall ideally lie between 10.5 and 11 at 28 days.	For the SCC, B50 CEM III/A 52.5 Rombas, B50 CEM III/A 42.5 Héming and B50 CEM I 52.5 Le Teil gave a pH of 11.8, 11.8 and 12.2 respectively after 28 days and a pH of 10.1, 10.2 and 10.3 after 90 days. For the shotcrete, B50 CEM III/A; B50 CEM I; and B40 CEM III/A gave a pH of 11.3, 11.4 and 12.3 respectively after 28 days. B50 CEM III/A and B50 CEM I gave a pH of <11 after 90 days.	Design basis needs to be changed to reflect the pH of the concrete leachate after 90 days, as the leachate chemistry is still evolving at 28 days. Note that the "28 days" is not critical – it comes from standard practices in the concrete industry.
FSSDS02	The maximum curing temperature of the concrete and shotcrete of containment walls shall not exceed 50ºC.	For the SCC concrete, the maximum curing temperature was 48.8ºC, and, therefore, the design specification was met. For the shotcrete, the maximum curing temperature was 66.7ºC, and, therefore, the design specification was not met.	Although the temperature criterion was not met by the shotcrete, further research may identify suitable materials that could be used to develop a suitable shotcrete mix (e.g. using CEM 1 rather than CEM III). However, based on the results of FSS, it is likely that SCC will be adopted as part of the reference design for seals.
FSSDS03	The strain as a result of shrinkage of the concrete shall be less than 350 µm/m at 90 days.	For the SCC concrete, the maximum strain was 284 µm/m, and, therefore, the design specification was met. For the shotcrete, the maximum strain was 633 µm/m, and, therefore, the design specification was not met.	As for the maximum curing temperature criterion, based on the results of FSS, it is likely that SCC will be adopted as part of the reference design for seals.

ID	Requirement / Design Specification	Compliance Assessment	Feedback to Design Basis
FSSDS04	Cracking of the concrete shall be minimised to be as small as possible.	For the SCC concrete, only minor cracking was observed, and, therefore, the design specification was met. In addition, the formation of cracks was minimised through the installation procedures (see DOPAS 2016b). For the shotcrete, significant radial cracking was observed, and, therefore, the design specification was not met.	At present, there is no quantitative value available for demonstrating compliance with this design specification and compliance must be judged qualitatively. Further development of the design basis could include development of a quantitative measure of cracking.
FSSDS05	The low-pH SCC shall have a characteristic compressive strength of at least 30 MPa at 28 days and 40 MPa at 90 days.	Measurement of the SCC compressive strength during material development (see DOPAS 2016b) gave a value of 37.8 MPa after 28 days and 50.7 MPa after 90 days. Therefore, the B50 CEM III/A mix was compliant with this design specification.	The design of the containment walls is not yet finalised, and this design specification is still under development. The current requirement specifies a standard achievable value. The strength of the concrete is also linked to the length of the walls which is dependent on other criteria such as technical feasibility and cost. Therefore, although the B50 CEM III/A mix has been shown to be compliant, it is too early to adopt this mix as a fixed part of the reference design.
FSSDS06	The low-pH shotcrete shall have a characteristic compressive strength of at least 25 MPa at 28 days and 35 MPa at 90 days.	Measurement of the shotcrete compressive strength during material development (see DOPAS 2016b) gave a value of 24±3 MPa after 28 days. Therefore, the B50 CEM I mix narrowly missed compliance with this design specification.	The design of the containment walls is not yet finalised, and this design specification is still under development. The current requirement specifies a standard achievable value. Further research may identify suitable materials that could be used to develop a suitable shotcrete mix even if their use underground should be limited and most likely discarded to build a monolith.

ID	Requirement / Design Specification	Compliance Assessment	Feedback to Design Basis
FSSDS07	The dry density of the bentonite materials used in the swelling clay core shall be 1,620 kg/m^3.	The dry density of the lower part of the core (~ 2/3 of the core) was 1,580 kg/m^3 and the dry density of the upper part of the core (~ 1/3 of the core) was 1,280 kg/m^3. This gave an overall average density across the clay core of 1,480 kg/m^3. In addition, the upper part of the last recess was not filled completely resulting in a gap of around 50 cm. The original 1,620 kg/m^3 was not achieved.	Investigation into the required swelling pressure undertaken during the FSS experiment concluded that a pressure of 5 MPa would be sufficient to meet the safety functions of the seal. This revised requirement could be met with an emplaced dry density of the bentonite materials in the swelling clay core of 1,500 kg/m^3. Therefore, as a result of the work undertaken in support of FSS there is a need to re-evaluate the swelling pressure requirement and subsequent bentonite dry density design specification currently used for seals in Andra's programme.

Implications for the Concrete Containment Walls

The main outcomes of the FSS low-pH SCC containment wall construction test are:

- The low-pH SCC mix is well suited to pumping and pouring of the monolith, as evidenced by visual inspection of the concrete as it was poured, i.e., the absence of any visible or significant (penetrating) cracks and entrapped air bubbles.
- The concrete pH values and mechanical properties are commensurate with (or better than) the pre-determined specifications.
- The shrinkage values and curing temperature measurements were also within the specifications for SCC.
- The operational cycle and the operational tools and methods used are compatible with "Cigéo" underground conditions.
- The SCC containment wall construction was undertaken with existing civil engineering technology, demonstrating that there is no requirement for novel technology developments for emplacement of such structures in a repository like Cigéo.

The result of the shotcreting was observed during operation and was judged to be mediocre since the temperature inside the shotcrete wall reached a higher value than specified (some 65°C instead of a maximum of 50°C). This somehow high temperature was due to the utilisation of too much hardener (incorporated at gun level) or/and to the incorporation of CEM I in the mix which is better than CEM III for spraying as it hardens more quickly, but has a high curing temperature. The following observations on the shotcrete wall were made:

- The shotcrete was far from perfect, with cracks and heterogeneous layers (too much rebound material incorporated to the monolith).
- A new mix for shotcrete needs to be developed in order to have a lower hydration temperature.
- New metric or plurimetric tests need to be implemented in order to optimise the shotcrete emplacement methods with a new mix.
- Metric cracks with an unknown origin were found in the shotcrete. The bottom part of the shotcrete wall was heterogeneous with poor structural strength. Care needs to be taken when cleaning the rebound. Increasing the mixing time for the shotcrete is expected to lead to better homogeneity.
- The use of shotcrete at large scale is not recommended and should be reserved to layer applications only, when there is a need for a handy use of low-pH concrete and then avoid the burdensome use of a formwork (a device needed for SCC) for a small volume.

The analysis work during dismantling has resulted in the following observations:

- Cracks were more numerous and open for the shotcrete containment wall.
- Cracks follow the direction of applying layers for the two containment walls.
- Except for the lower part of the shotcrete wall, no major discrepancies were noted in the shotcrete and SCC. A horizontally and slightly oblique fissure (relative to the sawing plane) was observed on the shotcrete.
- The poor quality of the bottom of the shotcrete is mainly due to the rebounds which were not totally removed (purged) by the operator between 2 layers (2 projections).
- Porosity variations are more significant in shotcrete than in self-compacting concrete. Neglecting the low porosity zones (in the lower part of the wall), resistance of the shotcrete is higher than the self-compacting concrete.
- The cracking is due to the shrinkage of the concrete. It is important to note that the withdrawal appears in the entire volume of the concrete (in three dimensions). The shape and size of the cracks are influenced by the ratio of dimensions of the containment walls.

Implications for the Bentonite Swelling Clay Core

The results obtained from the core emplacement were acceptable despite a longer than expected period of implementation (some nine weeks instead of the planned four). The dry density of the lower part of the core (~ 2/3 of the core) was 1580 kg/m^3 and the dry density of the upper part of the core (~ 1/3 of the core) was 1280 kg/m^3. This gave an overall average density across the clay core of 1480 kg/m^3 instead of the expected 1500 kg/m^3. The main reasons for the lower value are that the filling machine boom (auger conveyor in its pipe) was too big to move between support wall blocks and completely fill the upper part of the core. In addition, the upper part of the last recess was not filled completely resulting in a gap of around 50 cm.

Voids in the recesses would be unacceptable in Cigéo. A special procedure must be developed to fill the gaps in the recesses or at proximity of the support wall. Shotclay technology, as used in the EPSP experiment (in DOPAS), for the same purpose, is a promising candidate solution, even if its use may create (marginal) health issues (workers' protection with masks and overalls must be provided as for shotcreting).

The supporting wall, needed to contain the bentonite inside of the core, was built at the same time as the filling operations without any major problems. However, it was quite challenging to complete the construction of the support wall with the augers passing through it at the end of bentonite emplacement operations. To deal with this issue, it will be necessary to develop a specific method to fill the last part of the core. A small diameter gun, which can be easily moved by hand or by a specific robot, can be used to completely fill the last parts of the core volume with shotclay.

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 as far as its spatial variability is concerned. Therefore, additional work is needed in this area to further underpin the conclusions regarding the validity of the emplacement method.

The results obtained several months after the end of the core filling in a preliminary œdometric test for REM showed that with a dry emplaced density of 1510 kg/m^3, the swelling pressure obtained was just 3.88 MPa with the argillite (formation) water. This result has to be considered during further development of the seal design to verify if such a dry density could be sufficient to ensure appropriate performance of the clay core. This result has also to be confirmed on the long term and cross checked with the results from the metric scale REM experiment.

4.8 Conclusions on the FSS Experiment

The aim of the FSS experiment was to demonstrate the industrial feasibility of the emplacement of large volumes of bentonite (clay core) and low-pH concrete (containment walls) in a full scale seal. Andra is globally satisfied with the outcomes of the experiment and considers that the GME consortium, who was responsible for conducting the FSS experiment, has demonstrated this feasibility, even though Andra had to revise down the swelling pressure specification for bentonite performance (i.e., from 7 MPa to 5 MPa).

Andra considers that construction feasibility is now proven at a one-to-one scale. The low-pH SCC containment wall construction was undertaken with existing civil engineering technologies, demonstrating that there is no requirement for novel technology developments for emplacement of such structures in a repository like Cigéo. It was also concluded that low-pH shotcrete use in the repository should be discarded or minimised to be considered only in the building of the support walls or of the surrounding concrete liner support.

The feedback from this construction will be useful in defining the future full-scale seal tests to be conducted at the beginning of Cigéo during the Industrial Pilot Phase (and also in listing the “right” level of requirements). During this Pilot Phase (2025-2034), Andra will build a replica of the future real seal underground, but equipped with various monitoring systems (while no intrusive systems will be allowed inside the real Cigéo seal swelling clay core, at the time of its progressive closure).

5 Progress on the Technical Feasibility of Cigéo Seals

This chapter discusses the progress that has been made on the technical feasibility of repository seals during the DOPAS Project. This covers the work on the design basis, design, construction and performance in the experimental programmes carried out within the framework of the DOPAS Project, and particularly for FSS. The chapter is structured as follows:

- In Section 5.1, the application of systems engineering approaches during the DOPAS Project is discussed, and the benefits this has delivered to the design process, in particular the evaluation of designs against the design basis, are also discussed.
- In Section 5.2, the progress that has been made in demonstrating that the reference seal design tested in the DOPAS Project/ in FSS meet safety functions specified in Cigéo is presented.
- Section 5.3 discusses technical issues resolved during the DOPAS Project/FSS, focusing on the technical solutions for each of the components contained in seal design, the technical solutions related to construction, and technical solutions to monitoring the performance of seal components.
- Section 5.4 deals with the operational issues resolved during the DOPAS Project/FSS.

5.1 Application of Systems Engineering Approaches to Repository Design

The DOPAS Project has used a systematic requirements-based approach to defining the design basis for the plug and seal designs, and for evaluating the performance of the plugs and seals with respect to the design basis. The approach adopted is consistent with approaches adopted in other industries, but includes specific modifications suitable for application to the design of repository systems.

The development of parallel reference and experimental designs, as undertaken in the DOPAS Project is consistent with the practice of concurrent engineering.

The work in the DOPAS Project has demonstrated how a structured hierarchy of requirements can be a good basis for identifying and evaluating requirements at different levels of detail. In particular, the evaluation of the performance of the DOPAS experiments has focused on the evaluation of requirements expressed as both safety functions (which are also referred to as system requirements in the terminology adopted within the DOPAS Project) and design specifications.

In the evaluation work presented in this report, intermediate requirements are addressed by developing requirements at a lower (i.e. more detailed) level in the hierarchy. For example, the design specification related to bentonite hydraulic conductivity is expressed in terms of dry emplaced density. Design specifications should be expressed in a way that facilitates compliance demonstration, for example using quality control procedures during repository operation; testing of the bentonite density would be possible during repository operation but regular testing of hydraulic conductivity would be more challenging and would impact more significantly on repository operations.

This work has demonstrated how a structured approach to requirements management can be applied in repository design. The structured approach has been captured in the DOPAS Design Basis Workflow (Figure 3.**1**). Many programmes have been adopting requirements-based design approaches, but there has been little work published on the application of systems engineering through the iterative development of designs. In particular, the manner in which systems engineering approaches and structured hierarchies of requirements can be used to demonstrate compliance of repository designs with requirements and feedback into modified designs has not been illustrated with respect to repository systems previously. The work in the DOPAS Project, if adopted more widely by waste management organisations, provides an approach to using systems engineering in a more structured fashion in repository projects.

5.2 Demonstration that Designs Meet Safety Functions

Evaluation of the compliance of reference designs of seals with the design basis has been addressed in the DOPAS Project/FSS at two levels:

- Validation of performance against safety functions (system requirements), using a mixture of quantitative evidence and qualitative arguments.
- Verification of the performance of the experiments (of FSS) against design specifications using measurements and monitoring at a range of scales, including laboratory tests, mock-up tests and full-scale experiments.

5.2.1 Validation of Safety Functions

Work in WP2, WP3 and WP4 of the DOPAS Project has allowed the compliance of seal designs with safety functions to be evaluated. The conclusions for FSS are presented below.

The FSS experiment has helped to build confidence that the seal safety functions are met by the design tested within the frame of the DOPAS Project:

- For the Andra reference drift and ILW vault seal, the bentonite seal and the concrete containment walls have been successfully emplaced in the FSS experiment, showing that the design is technically feasible at full scale in Cigéo underground conditions.

5.2.2 Verification of Design Specifications

In the evaluation of the DOPAS experiments undertaken within the scope of the DOPAS Project, there has been a focus on key design specifications, which capture the most significant aspects of the performance of a plug/seal from the judgement of the experiment leader, and which relate to the design work and monitoring discussed in this report. Ongoing evaluation of the experiments undertaken within the DOPAS Project will be carried out by WMOs following the completion of the DOPAS Project, and will consider the full range of issues collated in the design basis.

However, the evaluation of the key design specifications undertaken as part of the DOPAS Project has demonstrated that the designs of plugs and seals implemented in the Project are consistent with requirements. Common key design specifications that are addressed in most of the design bases include:

- Compressive strength of concrete: The compressive strength of the concrete is a design specification recognised in the list of key design specifications for all experiments. This is because a key function of the containment walls (plugs) is to resist the pressures exerted on them. All experiments met this design specification, although this is because, in part, the compressive strength required was the strength assumed in design calculations. In some cases, mechanical properties like strength were known from the results of pre-existing testing and, in other cases, had to be verified during material development.
- pH of concrete leachate: For seals incorporating both concrete and bentonite components, and repositories in which leachate from the concrete can migrate and interact with other elements of the EBS (e.g. backfill and buffer), it is important that the concrete leachate does not affect the long-term performance of the bentonite. This can be achieved by developing a concrete with a leachate pH in relevant ground waters of ≤ 11.
- Curing temperature of concrete: For the hydraulic performance of the concrete in containment walls (plugs), it is important that the concrete does not crack during curing. Absence of cracking owing to thermal stress is ensured by specifying a maximum curing temperature, the value of which is dependent on the design of the concrete in the plug or seal. In addition, cracking of concrete can result from external stresses, and the absence of crack formation can be monitored using strain gauges and/or through visual inspection of exposed surfaces of the concrete.
- Dry emplaced density/swelling pressure of bentonite: The hydraulic performance of bentonite sealing sections within the DOPAS experiments is defined by key design specifications related to bentonite dry emplaced density. Compliance with bentonite density requirements in the FSS experiment has been demonstrated using mass balance quality control approaches.

5.3 Technical Issues Resolved in the DOPAS Project/in FSS

The DOPAS Project has addressed a large number of technical issues associated with the design and emplacement of materials and monitoring systems for plugs and seals, and also the siting and construction of plug and seal locations. The achievements in the DOPAS Project with respect to these issues are discussed below for the FSS experiment.

5.3.1 Siting of FSS

Siting of the plug and seal locations for the DOPAS experiments has been based on a variety of approaches. The FSS experiment was sited in a surface facility owing to cost, logistics and monitoring considerations. Siting of the full scale demonstrators in Cigéo ramps and drifts is still under consideration, since the Cigéo general architecture is not frozen yet.

5.3.2 Bentonite Core

For several plug and seal designs, bentonite components provide the primary sealing function. These include the reference drift and ILW vault seal in Andra's Cigéo repository.

In the DOPAS Project, the technical feasibility of several different types of bentonite seals (swelling clay cores) has been demonstrated:

- An admixture of bentonite pellets and crushed pellets has been successfully installed in the FSS experiment with an average density of 1480 kg/m^3. Although this did not meet the original specification of 1620 kg/m^3, re-evaluation of the performance of the bentonite admixture has indicated that the required swelling pressure of 5 MPa can be achieved with an admixture dry density of 1500 kg/m^3.
- Significant learning regarding the emplacement of bentonite admixtures was achieved during the FSS experiment. This included, for example, the arrangement of the augers and the need for the conveyor arm to be designed to better fill the top of the tunnel. This latter development is considered to be readily achievable, and, therefore, the achievement of suitable bentonite densities is considered to have been demonstrated in the FSS experiment.

Overall, the work on bentonite swelling clay core in the FSS has identified a range of designs that could be utilised in specific situations. In France, pellet-based systems are preferred, as they are judged to represent an efficient industrial method of emplacement in clay host rock systems, such as the Callovo-Oxfordian Clay in which the Andra drift and ILW vault seal will be constructed.

5.3.3 Concrete Containment Walls

A wide range of concrete containment walls (plugs) have been tested in the DOPAS Project experiments:

- In the FSS experiment, Andra tested two concrete containment walls, one constructed from SCC and another constructed from shotcrete.

Work on concrete materials in the DOPAS Project has allowed the development of several concrete mixes with excellent properties for application in repository plugs and seals:

- In the FSS experiment, the concretes include binary mixes of cement and silica fume (FSS SCC wall), and a ternary mix of cement, silica fume and blast furnace slag (FSS shotcrete wall).

The concrete mixes incorporate a range of aggregates and additives to achieve the necessary properties and workability. Experience has demonstrated the need for procedures to respond to quality control measurement of concrete properties prior to application, for example the ability to add additional superplasticiser to meet slump flow requirements and the need for appropriate temperature control prior to, and during, emplacement.

All of the concrete mixtures were designed so that the concrete leachate waters would have a reduced pH. The pH values of leachate water generated from the concretes used in FSS were less than 11 (at 90d).

The SCC concrete developed in FSS met a wide range of performance criteria, including, low-pH leachate, workability, and low temperature during hydration, acceptable pressures on formwork, appropriate shrinkage and long-term durability. This performance demonstrates the suitability of the mix for application in Cigéo. Evaluation of the performance of the concrete mix at full-scale has demonstrated good scalability of concrete properties.

Many lessons have been learnt during the DOPAS Project regarding the emplacement of concrete materials. SCC has been used successfully in FSS, but requires the erection and subsequent removal of formwork, which must be factored into the operational schedule if SCC is used in the repository. In contrast, shotcrete walls can be emplaced rapidly without the need for additional structures, but emplacement of shotcrete is dependent on operator's skill and can be affected by rebound leading to variable properties throughout the walls.

The metric mock-up tests proved beneficial for addressing the concrete recipe formulations and thus improvements were made prior to full scale emplacement operations.

5.3.4 The Plug/Seal-Rock Interface

The DOPAS Project has also tested specific grouting procedures, with preliminary grouting of the outer regions of the plug/seal-rock interface at relatively low pressures followed by higher pressure grouting of central sections of the interface.

A particular issue addressed by the FSS experiment is the filling of potential break-outs in the argillaceous host rock of the Cigéo repository. Work during the mock-up tests evaluating bentonite emplacement has developed the techniques that will be used to ensure the filling of these parts of drift and ILW vault seals. These developments include reduction in the breakages of the bentonite pellets and changes to the physical arrangements of the screw augers.

5.3.5 Temporary Structures

The full-scale experiments in the DOPAS Project have illustrated the importance of temporary structures in the overall feasibility of installation and performance of plugs/seals.

Temporary structures are used to facilitate emplacement and include the delimiters between the main functional components and the formwork used for pouring SCC[1].

The temporary structures designed and utilised in FSS have performed well.

5.3.6 Monitoring Systems

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

- Temperature in concrete.

[1] These structures are referred to herein as "temporary" structures as their function is only to temporarily support other components on the plug/seal system during installation.

- Total pressure and pore pressure (applicable to REM, not to FSS).
- Strain and displacement.
- Relative humidity.
- Ambient temperature.

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.

5.4 Operational Issues Resolved in the DOPAS Project

The DOPAS Project has addressed a large number of operational issues associated with the construction of plugs and seals. The achievements in the FSS experiment with respect to these issues are summarised below.

5.4.1 Health and Safety during FSS Construction

FSS has addressed several issues associated with health and safety during the construction of plugs and seals. In particular, the practical experience of constructing seal components at full-scale has allowed experience to be gained in the hazards posed by working in restricted spaces, sometimes with multiple individuals performing separate tasks.

Consideration of safety during construction and installation is paramount and provides an important constraint on design and operational schedules. For plugs and seals, protecting workers against the potential for rock fall has a significant impact on design. An example is the reduced length of drift support that can be removed from the location of Andra's drift and ILW vault seals compared to shaft and ramp seal, owing to the relatively low competency of the Callovo-Oxfordian Clay host rock in the location (some -500m of depth) of the horizontal seals.

Another lesson learned from the conduct of the DOPAS experiments is the management of dust during the installation of the bentonite mix, especially the dust created by the transfer of the bentonite powder. Dust generation (as envisaged in Cigéo) can be mitigated through the use of enclosed bentonite conveyance methods and by water spraying during installation.

5.4.2 Logistical Issues Associated with FSS Construction

The experience from FSS has demonstrated the impact of logistical issues on the installation of the seal components. In particular, the need for back-up machinery to be utilised during routine maintenance or to counteract delays owing to unexpected failure is good practice.

During the planning of the FSS experiment schedule, it was considered good practice to involve contractors early in discussions, as they can have valuable experiences that should be taken into account when scheduling work. Contractors should be provided with clear definitions and justifications for requirements and design issues, so they understand the impact of logistics and construction works. This is also important during the procurement phase for supply contracts, and for later work acceptance/approval to progress.

5.4.3 Project Management during FSS Construction

The DOPAS Project has illustrated some of the complexity that will need to be addressed during the industrialisation of seal construction and installation activities during repository operations. The installation of the seal components requires many activities, and, therefore, there is a need to develop simple and repetitive commissioning methods. Much of the work in the DOPAS Project has been of a “one-off” nature, but this experience has been useful to identify where routine application of methods can be undertaken.

6 Remaining Technical and Operational Issues

This chapter discusses the remaining technical and operational issues that need to be addressed prior to the implementation of seals during repository operation. The structure of the discussion mirrors that used to discuss the progress in DOPAS / in FSS:

- In Section 6.1 remaining issues associated with the application of systems engineering approaches during the DOPAS Project is discussed.
- Section 6.3 discusses remaining work on operational issues associated with industrialisation of seals construction in Cigéo.

This discussion is focused on the long-term resolution of technical and operational issues in preparation for finalising the designs of the Cigéo full scale seal demonstrators in conjunction with the start-up of the Cigéo pilot phase operations.

6.1 Further Development of Systems Engineering Approaches in Repository Design

In the DOPAS Project, the design bases for plugs and seals were initially collated using a bottom-up process without the application of strict definitions of the requirements and conditions to be included at each level in the hierarchy. This allowed identification of a hierarchical structure applicable to all of the plugs and seals considered in the project (including FSS), and its application in the evaluation of each experiment performance. The work has illustrated that requirements can be structured into a common hierarchy that is developed in parallel with the development of designs. Further work on the design bases of plugs and seals could include structuring of the requirements and conditions into hierarchies that include full and explicit links and dependencies between all of the requirements on plug and seal design.

In addition, the work on requirements, although focused on plugs and seals, is thought to be generic, i.e. the DOPAS Design Basis Workflow (Figure 3**.1**) could be applied to the development of design bases for all elements of the multi-barrier system and to the components of each of the sub-systems. However, it must be recognised that development of comprehensive design bases in formalised hierarchies containing all of the links between the requirements is a highly-intensive process. Parallels could be drawn with the development of data bases of features, events and processes to underpin safety assessment models; although the development of these data bases was originally viewed as a method for defining the scope of assessment models, their use is now more widely applied to cross-checking the completeness of the models. Similarly, further application of systems engineering principles in repository programmes may lead to the conclusion that requirements hierarchies are best applied in cross-checking of design specifications rather than in their development.

This raises the question of what level of detail is required in a design basis like that of the Cigéo seals. Several of the design bases included in the DOPAS Project referred to standards, codes of practice or other control programmes. General reference to other more detailed procedures helps to keep design bases manageable, but visibility of some of requirements may be lost. Therefore, a process (or argument) is needed as a basis for the inclusion of requirements (and conditions) in a design basis. Four reasons for including a requirement in a design basis are proposed:

- Supports licensing, the traceability of decisions and demonstration that the seal design meets the necessary safety performance requirements.
- Supports development of a construction contract / tendering process.
- Supports demonstration of construction feasibility and by this provides the concerned WMO with confidence in the approach adopted.
- Has direct impact or relationship to operational safety.

This identifies 3 audiences for a design basis: regulators, contractors and the WMO, and may help to guide the level of information required in a design basis as they are further developed in the future.

Further work on the use of systems engineering in repository programmes (in Cigéo) could also consider the following questions:

- How will the work on full-scale testing (in DOPAS) be used to develop design bases and construction procedures that can be followed in the repository (and at first for the construction of the Cigéo seals full scale demonstrators during the Pilot Phase around 2025/2034)?
- How can a requirements-based design be developed from a research activity to a process used to manage the industrial implementation of geological disposal (of Cigéo)?

Reference designs can be modified in response to the results of the DOPAS experiments (of FSS) and supporting research. The modification of the reference designs is an important step in the application of the results of the DOPAS Project in each WMO programme.

Finally, extension of the systems engineering work undertaken in the DOPAS Project should give greater consideration to a broader range of requirements. The work in the DOPAS Project has concentrated on safety functions and design specifications linked to these safety functions (e.g. hydraulic conductivity and strain of concrete structures). Other requirements such as reliability and reproducibility, requirements on operational safety and operational constraints (logistics) and on the environment in which plugs and seals are constructed will need greater consideration going forward.

6.2 Remaining Technical Issues for seals in Cigéo

6.2.1 Siting of Seals

Application of methodologies for determining the number and the specific positions of seals needed in Cigéo remains a pending issue. Besides, there will have to be further developments to the procedure used for preliminary preparation of the drift / vault liner deposition, or the requirements or design will have to be modified to allow for the potential switch from the reference seal design (as explored with FSS) to the alternative seal concept (including an hydraulic “cut-off”).

Furthermore, the DOPAS Project has highlighted the need for additional development of requirement statements related to the EDZ in the location of seals. Requirements (tolerances) on the shape and surface state of the rock recess walls (after local deposition of the drift/vault concrete liner) are required.

6.2.2 Excavation of Seal Locations

Wire sawing, and wedging and grinding have both been shown to be feasible techniques for construction of specific parts of the seal components. However, these techniques require further refinement before they can be applied in the repository.

6.2.3 Bentonite Swelling Cores

The use of pre-compacted blocks and powder-based admixtures have both been demonstrated as suitable physical forms for bentonite used to provide low hydraulic conductivities in plugs and seals. In all experiments undertaken in the DOPAS Project, challenges have been encountered when installing bentonite materials close to the roof of tunnels, and specialised routines for filling these parts are required. Although required bentonite densities have been achieved by the installation procedures applied in the DOPAS Project experiments, there has been (sometimes significant) spatial variability in emplaced dry density of bentonite, and requirements on emplaced density and/or further understanding of homogenisation processes are needed as disposal programmes move forward (in the case of Cigéo, the feedback from the REM experiment will be very helpful).

6.2.4 Concrete Containment Walls

As discussed, a range of low-pH concrete mixes have been developed and successfully tested in the DOPAS Project. The results from the FSS experiment have demonstrated that SCC mixes that meet design specifications are available for application in the repository, but shotcrete recipes require further work (e.g. to reduce the incidence of rebound or the temperature during hardening). Nonetheless, further development of shotcrete recipes may benefit some programmes, as shotcreting can, in some circumstances, be employed relatively easily (e.g. without the need for formwork).

Further work on concrete walls also requires the development of optimised delivery routines and other logistical issues that fully consider the full range of operational activities occurring in the repository at the time of delivery, and, for some programmes, elaboration of the acceptance criteria to be applied during repository operations.

6.2.5 The Wall/Core-Rock Interface

The experiences from the FSSS experiment have 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).

6.2.6 Temporary Structures

Temporary structures include the delimiters used to separate and support installation of the seal components, and the formwork against which SCC is poured. All of the temporary structures have performed well in the DOPAS Project experiments. Further work on temporary structures is mainly focused on developing the final detailed and optimised designs for industrial applications.

6.2.7 Monitoring Systems

Relatively detailed monitoring systems have been used to track the performance of the DOPAS experiments and to demonstrate consistency with requirements. However, any monitoring of plugs and seals in repositories 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 a repository could affect both the post-closure performance of the system and the schedule for 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 systems engineering-based approach used to evaluate performance of the experiments in the DOPAS Project provides a method for identifying the monitoring systems that could be applied in a repository, as it provides an explicit discussion of the evidence on which compliance with requirements is based in order to underpin statements that the design meets requirements. This approach could be further developed as a basis for developing the requirements on monitoring system design.

6.3 Industrialisation of Plugging and Sealing

As discussed above, the DOPAS Project has contributed towards demonstration of the technical feasibility of plugs and seals. However, the results of the experiments need to be used in the development of industrial solutions for installing many tens of plugs and seals in each repository constructed. 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.

Industrialisation will require the transfer of the lessons from the full-scale DOPAS experiments to the repository. This may involve further full-scale testing of revised reference designs in the repository 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 construction materials in the future (i.e. decades later), the instrumentation required to directly monitor plug/seal behaviour, and how these data will be used in future decision making.

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

Future work requirements also include the potential adaption/up-scaling that is required to implement the sealing solutions studied to an operational repository. This includes both technical and economic appraisal, considering aspects such as manufacturing considerations, construction methodologies including deployment (remote or man access), testing and verification, programme duration, manpower’s skill and training and finally costs.

7 Conclusions

WP2, WP3 and WP4 of the DOPAS Project have included:

- Collation of the design basis for the plugs and seals considered in the DOPAS Project, conceptual and basic designs, and the strategy adopted in programmes for demonstrating compliance of the designs with the design bases.
- Detailed design, site selection and characterisation, and construction of the experiments.
- Evaluation of the performance of the full-scale experiments and evaluation of the conclusions from the experiments conducted in the DOPAS Project with respect to the technical feasibility of constructing the reference designs.

The experimental programmes undertaken in the DOPAS Project have been successful. By the time of the freeze date for this report, all four of the full-scale tests have been designed and constructed. Initial evaluation of performance has been undertaken.

For FSS this performance evaluation has been in response to monitoring during installation of the seal components and after dismantling. In all cases, the evaluation of the experimental results with respect to the safety functions and design specifications has demonstrated that the results obtained are consistent with the design basis.

All of the plug/seal design programmes have had to respond to challenges during the conduct of the experimental work, and this illustrates the need for flexibility during the planning for full-scale tests and demonstration work.

The achievements in the DOPAS Project include the following:

- Development of a structured approach to requirements hierarchies which are applicable to all waste management programmes.
- Development of a structured approach to development of designs in parallel with development of the design basis (concurrent design); the approach has been captured in the DOPAS Design Basis Workflow.
- Development and application of techniques for siting repository plugs and seals.
- Application and assessment of techniques for construction of plug/seal slots to high specifications.
- Successful demonstration of the application of low permeability bentonite seals in the FSS, EPSP and DOMPLU experiments.
- Successful demonstration of the application of low-pH concrete containment walls, utilising either SCC or shotcrete.
- Further development of contact grouting materials and approaches.
- Successful demonstration of the application of delimiters and formwork to aid the installation of plugs and seals.

- Successful monitoring of the performance of plugs and seals using existing monitoring technologies.
- Addressing concerns regarding health and safety by modifying proposed approaches to plug slot excavation.
- Addressing issues with logistics and project management to successfully construct plugs and seals within the timeframe of the Project.

In addition, the work in the DOPAS Project has allowed consideration of the remaining issues associated with plug/seal design and the next steps in industrialisation of plug/seal installation.

Key recommendations for further work that have been identified in the DOPAS Project include:

- Wider use of the structured design basis development methods developed in the DOPAS Project, including application of the DOPAS Design Basis Workflow, both in terms of the adoption of systems engineering by more WMOs and use of the DOPAS Project approaches for other elements of the multi-barrier system.
- Use of the results from the DOPAS Project to revise reference designs for plugs and seals, and to consider the compliance of the revised designs with the design basis.
- Further clarification on the requirements on the rock adjacent to plugs and seals to support the siting of the structures.
- Consideration of the application of plug/seal slot excavation techniques to the site-specific conditions to be found in repository sites.
- Evaluation of the requirements on bentonite homogeneity and greater understanding of homogenisation processes for bentonite seals used as part of plug/seal design.
- For SCC, optimisation of delivery routines and logistical issues needs to be considered as part of the industrialisation of plugging and sealing.
- For shotcrete, improved mixes and delivery methods (e.g. reducing rebound to ensure a more homogeneous product) are required before application in repositories.
- Development of plans for monitoring of plugs and seals which are based on relevant and measurable parameters, and are linked to the needs of the safety case.
- Undertaking work to industrialise the process of plug/seal implementation, including development and documentation of construction processes and quality control programmes.

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