Document technique/ *Technical Document*

Identification / *Identification*

DRPAS3C190095

Nom du FDR / *FDR Name* : HAVL Argile

Diffusion* / *Distribution* : Limitée

Émetteur/*Originator*	**Date d'origine :**	**Page**
DRD/3C	15/02/2019	1/104

Synthesis of 20 years Research, Development and Demonstration in Andra's Underground Research Laboratory in Bure for Cigéo Project - France"

Documents associés /*Associated documents* :

Ind. *Ind*	**Date** *Date*	**Nom/visa du rédacteur** *Written by [1]*	**Nom/visa vérificateur** *Reviewed by [1]*	**Nom/visa approbateur** *Approved by[1]*
A	01/03/2019	J. Delay	E. Huret	F. Plas

Révisions/*Review*

Ind./*Ind*	Date/*Date*	Modifications/*Change*
A	01/03/2019	First issue

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1. Foreword and Introduction

Since 1991 and its creation, Andra has been carrying out the research linked to the management of high level (HA - HLW) and intermediate level long lived (MA-VL – ILLW)) radioactive waste in France. The French Deep Geological Repository (DGR) project is called “Cigéo” project (Centre Industriel de stockage GEOlogique[1]).

Since 2000, the project for the development of Cigéo has been supported by a research and development (R&D) programme that included the construction and operation of an Underground Research Laboratory (URL) in a deep clay formation (Callovo-Oxfordian) as host rock. Prior to that, the clay formation was recognized via surface investigations (seismic survey…) and boreholes. The knowledge acquired step by step by Andra while operating the URL has been used to develop progressively the Cigéo project in link with the major milestones.

The URL (also called Bure URL) was licensed for construction in November 1999. Its main purpose was to give access, in real repository-like conditions, to the regionally identified clay host rock formation expected to be favourable a deep geological disposal to guaranty the long-term safety of high level and intermediate level long lived radioactive waste.

The URL in the Andra’s Meuse–Haute-Marne Research Centre (CMHM)[2] lies on the border of the Meuse and Haute-Marne districts on the eastern boundary of the Paris Basin (Figure 1). On the site, the Callovian–Oxfordian argillaceous layer is about 130 meters (m) thick and lies at a depth of 422–552 m. Construction began in August 2000. Two shafts provide access to two levels of drifts at depths of 445 and 490 m (Figure 4).

Figure 1 Location of the French URL

[1] The name Cigéo was adopted in 2009
[2] The CMHM comprises the URL, a technological exhibition facillity and an Environmental Bio Bank

The geology of the Eastern Parisian Basin, at the north of the Haute-Marne district and south of the Meuse district is simple, homogeneous and predictable. It comprises sequences of continuous limestone, marls and argillaceous layers slightly dipping toward the current centre of the sedimentary basin (Figure 2). The detailed study of seismic geophysical profiles of the sector shows that the tectonic deformations affecting the region over the past 150 Ma have been mild and essentially limited to the Gondrecourt fault system and the River Marne fault system located at the boundaries of the area of interest. Between these faults, the sedimentary structure of Callovian-Oxfordian formation is homogeneous. The clay minerals stratigraphy of the Callovo-Oxfordian consist of illite and mica, interstratified with illite/smectite, kaolinite and chlorite layers.

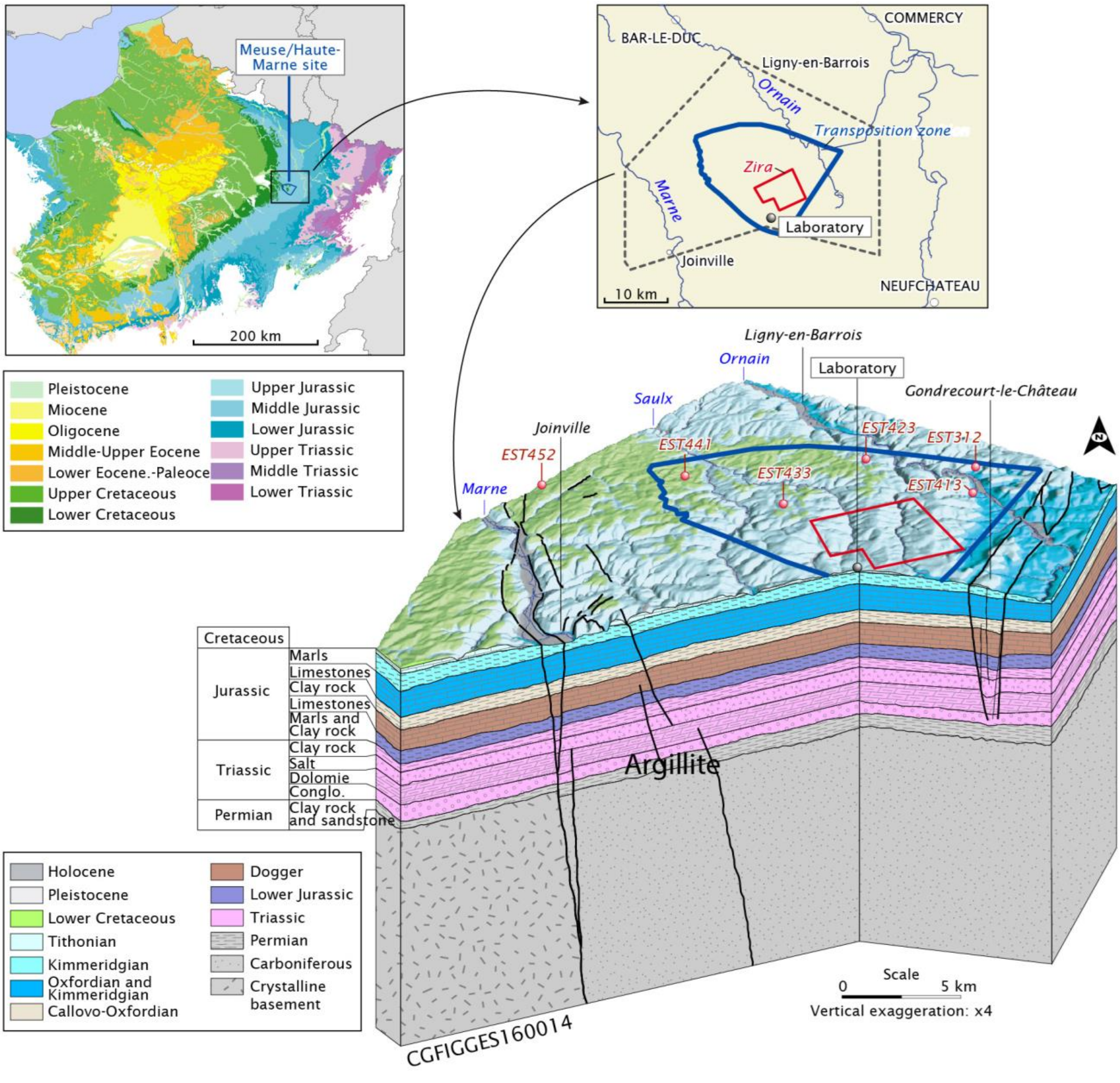

Figure 2 *Geological context of French URL*

Prior to the construction and later during the operation of the URL, geoscientific research programmes have been carried out to provide data for regional geological and hydrogeological modelling. More than fifty deep geological boreholes have been drilled. Most of them were cored and tested and logged, (Figure 3)

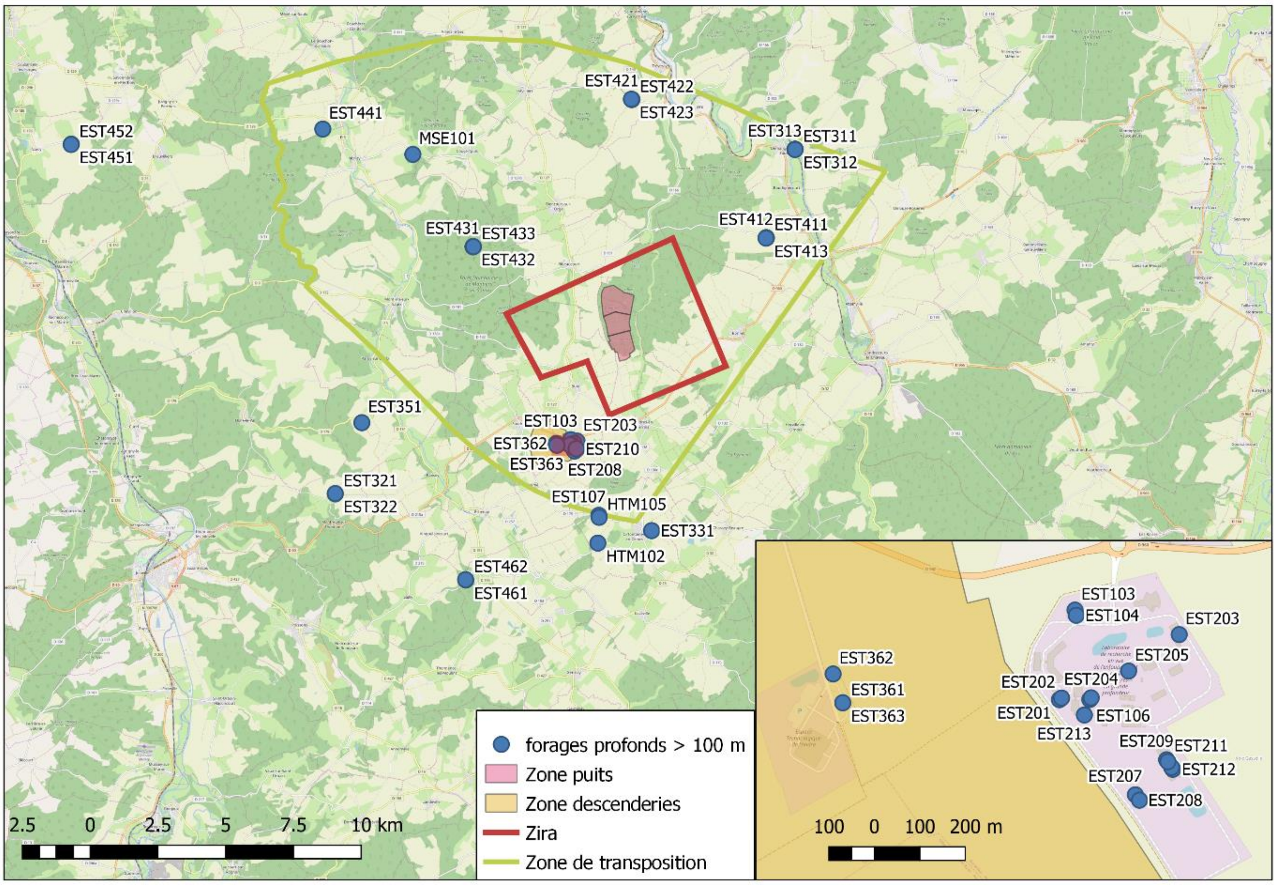

Figure 3 *Deep boreholes drilled prior to URL construction and during its operation – the picture shows the footprint of the URL on the bottom right of the figure, in green line the definition of the zone (call ZT) for that the feasibility principle of Cigéo was demonstrated in Dossier 2005 and in red line the footprint (call ZIRA) of the Cigéo underground disposal facility*

From 2004 to 2019, 1700 m of scientific and technical drifts up to 9 m in diameter were excavated in the URL (Figure 4). Four technical excavation means have been used (drill and blast, pneumatic hammer, road header, and tunnel boring machine with segment erectors). Many techniques for lining and supporting the drift walls have also been tested (steel arches, bolts, shotcrete with or without reinforcement, and segments).

These drifts have three main purposes (i) circulation and access to experimental and technical zones, (ii) technical areas (safety niches, power supply niche, cement preparation niche), and (iii) experimental zones.

The main level of the URL is implemented in the middle of the Callovo-Oxfordian formation where the clay content is at is maximum (55%). This level is also the level defined for the waste disposal vaults. In the URL, the drift at 455m aimed at starting the experiment programme in the upper part of the layer and allow the setting up of the REP experiment dealing with the host rock behaviour during shaft excavation.

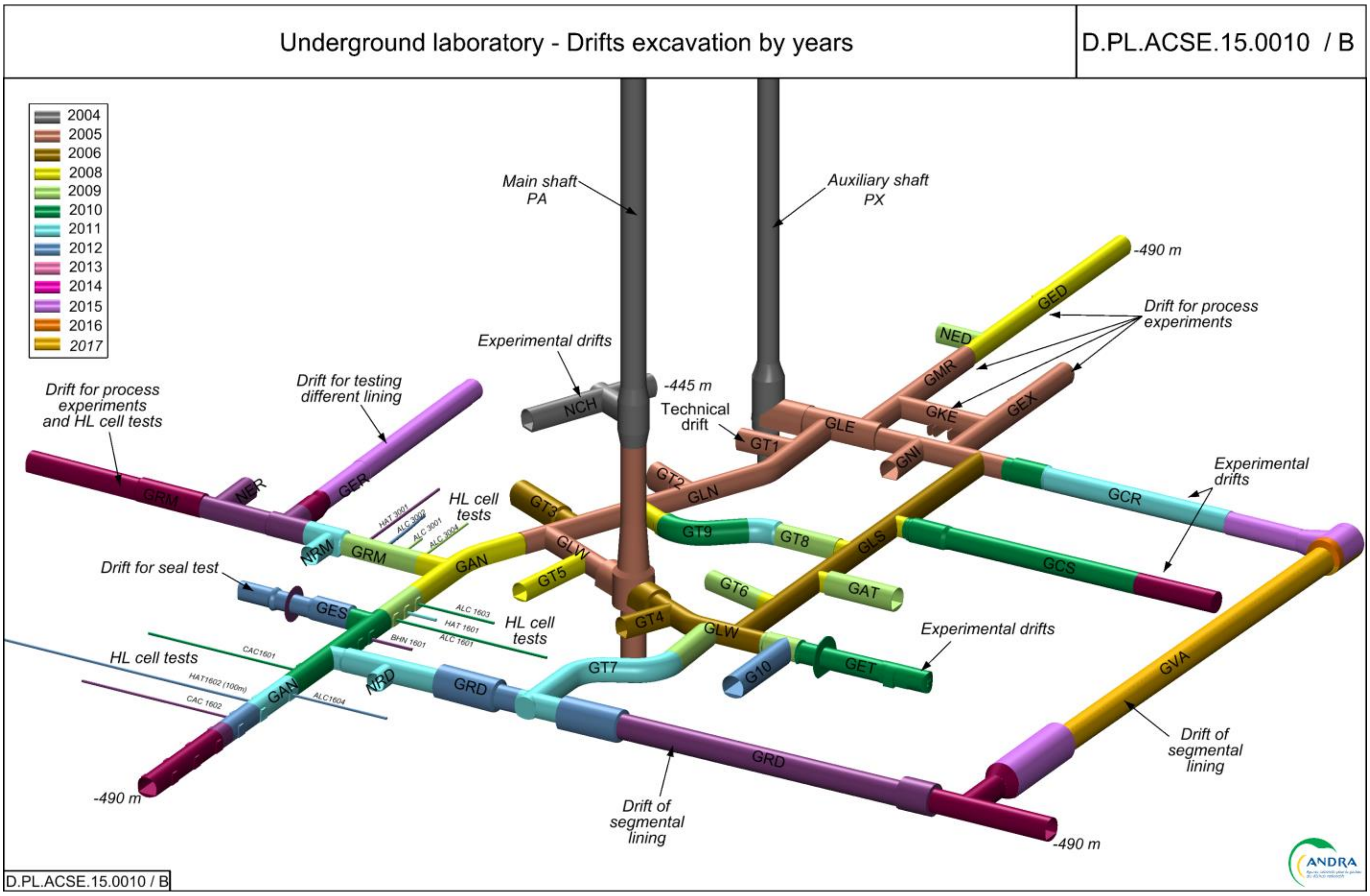

Figure 4 Overview of the URL drifts development by years from 2004 until 2017

More than 850 boreholes have been drilled from the drifts providing 8000 m of core for geological survey and laboratory analysis (58,000 samples). More than 10,000 sensors are monitored in real time on an integrated data acquisition and management system (SAGD/DAS). The system displays and holds records of all of the data acquired since the experimental drifts were put into service. It is also used for monitoring the environmental parameters that may influence the phenomena observed (temperature, hygrometry, effects of excavation in adjacent drifts, etc.).

Looking back over more than 25 years of URL construction and operation, three main phases can be defined in close relation with the milestones of Cigéo project development plan. The first one that took place from 2000 to 2005 is the confirmation of the intrinsic favourable properties of the Callovo-Oxfordian clay to demonstrate the feasibility principal of Cigéo project, in particular for long term safety. The second one from 2006 to 2010 was mainly focused on the deeper characterization of the disturbance that would be generated by the repository on the Callovo-Oxfordian and the behaviour of engineering components (steel, concrete, glass…). The third one from 2010 to 2015 consisted of firstly testing construction and operation options in order to design a reversible repository that could be safely closed and sealed at the end of a century long period of operation.

The current phase started in 2016 aims at providing additional scientific and technical evidence to support the license application of Cigéo project, including its instruction.

This report proposes an overview of these 25 years of French URL development. It will present the drivers of the scientific and technological R&D programmes and how these programmes were up-dated and set up to accompany the development of Cigéo project. To illustrate the purpose of the report, the four R&D investigation phases of the URL are described with selected example R&D key experiments designed, implemented and performed.

The annex presents additional details of these selected experiments.

2. Setting Up the Scientific and Technological R&D Programmes, Including URL Activities

The basic strategy and roadmap for definition of Scientific and technological R&D programmes of URL, as part of overall Andra's R&D programmes, were driven by the legal framework voted by the French Parliament. The laws implied submission of reports that paved the way of Andra's technical and scientific approach for the development of Cigéo project (Figure 5).

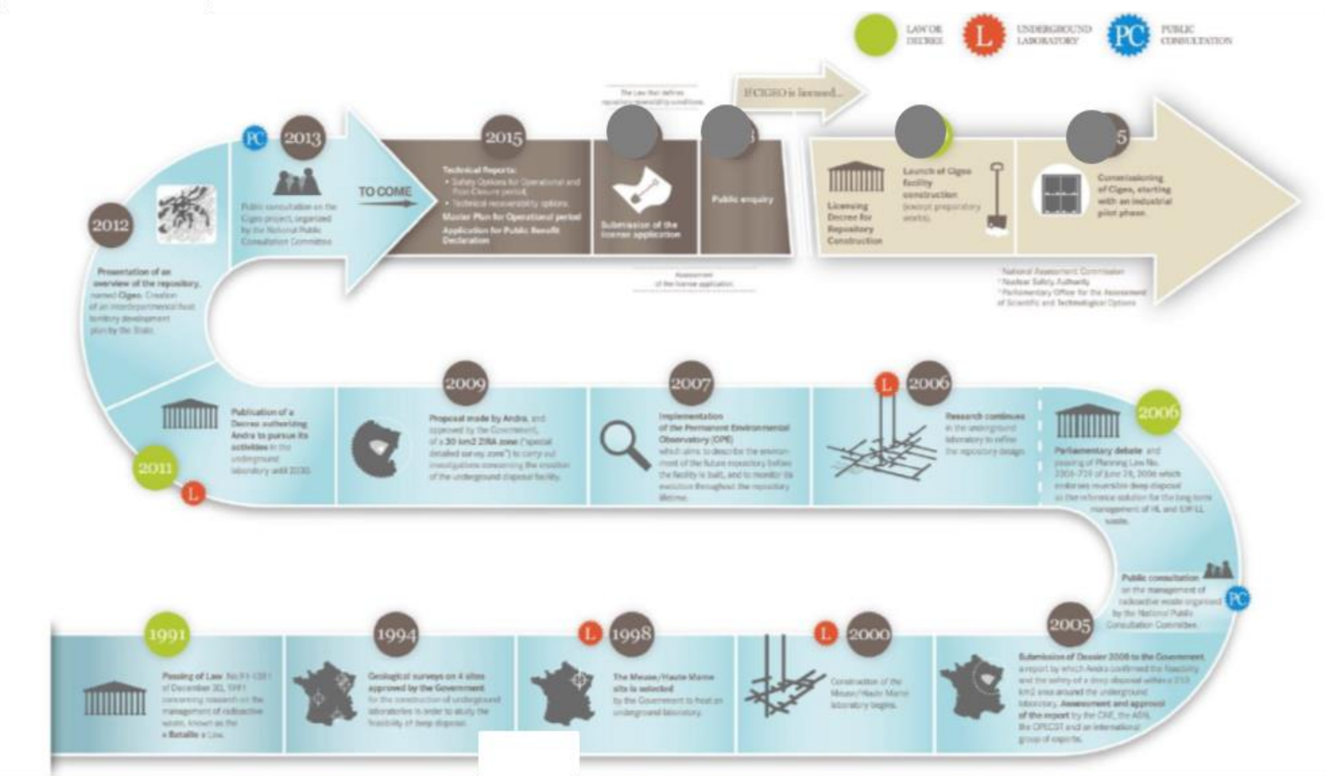

Figure 5 Global overview of the Gigéo development process

2.1 The Legal Framework

The general principles of radioactive waste management have been set initially by the December 30th 1991 Waste Act (called as well "Loi Bataille") and later modified by the 2006 Planning Act on the sustainable management of radioactive materials and waste.

2.1.1 Programme Act 1991: Feasibility principle of the deep Geological Disposal for the long term management of HLW and ILLW

Andra was created by the 1991 Law as a state-owned body in charge of the radioactive waste management, including the design and operation of waste disposal facilities.

As for high- and intermediate-level long-lived waste that has no operational disposal solution to date, three research axes were given: (i) possibility of partitioning and transmutation, (ii) long-term storage, and (iii) geological disposal (the notion of reversibility has not yet been introduced).

Andra was in charge of the third research axis. A period of 15 years was given to achieve conclusive results in each area, and then a report would be prepared and submitted to the government. In its turn, the government would assess the research conclusions and would publish an evaluation report that would compare the three outcomes and recommend the most optimal future way of High-Level Waste (HLW) management. This would give rise to a project of a new law on waste management where conditions for chosen waste management directions would be consolidated and made official.

To carry out the research on this third axis, Andra needed facilities and developed scientific cooperation to perform tests and experiments on a geological medium in a given area. The aim was to determine whether geological properties were suitable for the disposal of the high-level radioactive waste and to assess the feasibility of a disposal from the safety, technical, and economic points of view.

In order to build research laboratories Andra had to comply with a number of official requirements. For instance, Andra had to organise public consultations prior to preliminary site surveys. It consisted on taking into account the position of local authorities as well as of those on the district and regional levels by supplying all documentation and data necessary for URL construction license application. Andra had also to draw perspectives for the sustainability of technical competences and financial resources. These financial resources should be sufficient in order to ensure the entire facility lifecycle - from design through operation and closure to dismantling.

After 15 years of research, Andra submitted a report (Dossier 2005) that established the feasibility principle of a deep geological disposal for HLW and ILLW[3] in the Callovo-Oxfordian argillaceous formation on an area of about 2050 km² around the French URL: this feasibility comprise the demonstration of long term safety and the capability to construct, operate and seal the geological disposal, based on a design concept (overall architecture, disposal cells, disposal packages, backfill, seals…).

2.1.2 Planning Act 2006: geological disposal as reference solution for long term management of HLW and ILLW - Disposal Facility Safety and Technical Design – to submit a licensing application

The Planning (or Programme) Act of 2006 on the sustainable management of the radioactive waste and materials was based on the conclusions of the 15-year research in the three axes given in the 1991 Act. A disposal in the deep geological layer (meaning "clay") was chosen as a reference solution for the long term management of high-level and intermediate long lived waste. A principle of reversibility was defined. It was to be integrated into the design and overall Cigéo project development. As for research in two other research axis of the 1991 Act, it was to be continued in support to the reference solution.

In addition, the Act prescribed reduction of the volume and of the harmful nature of the waste. This would be achieved by processing and conditioning.

As for Cigéo project, some milestones were set to the license application and start of operations. A public debate and reports were set to be issued by Andra in 2015 to be submitted to the regulatory authorities for review (Nuclear Safety Authority - ASN, Parliamentary Office for Scientific and Technical Choices Evaluation - OPECST, French National Assessment Board - CNE).

2.1.3 Taking Into Account Reversibility

In July 26, 2016, a new law gave details on conditions for creating a reversible repository for high- and intermediate level long-lived waste in a deep geological layer.

The reversibility is defined as "the ability of successive generations to either pursue construction then operation of consecutive phases of a repository, or to reassess earlier decisions and modify management solutions." Reversibility offers, for at least 100 years, a possibility of multi-generation decision process and project governance.

[3] Spent fuel were also studied, whether the French reprocessing strategy were to evolve

The implementation of the reversibility principle shall be reviewed every 5 years during the operation of the facility. Further on, in order to ensure the citizen participation in the facility running and operation, an Operations Master Plan (named PDE) shall be developed and updated every 5 years in cooperation with stakeholders and the public.

Moreover, the operating license is also subject to the reversibility principle that needs to be demonstrated. The reversibility is supported by project management guidelines to allow an incremental development and a gradual construction of the repository, *i.e.,* retrievability, of the disposed waste packages if ever it becomes necessary.

2.1.4 Basic Safety Guide on deep geological disposal

In the framework of its regulatory functions concerning Base Nuclear Facilities (INB) safety, the Nuclear Safety Authority (ASN) issues decisions and guidance defining the safety objectives to be achieved by INB operators. In addition, it describes accepted practices compatible with these objectives. In the past, ASN used to issue basic safety rules so-called "RFS," some which are still valid and other under revision.

Thus, in 2008, ASN issued a Safety Guide on radioactive waste management that replaced the former RFSII.2.f. The new guide took into account the work carried out by Andra during the 1999 - 2006 period and the requirements of the 2006 Act.

This Safety Guide contains the main safety objectives to design and build the deep geological disposal in order to ensure its safety in the post-closure term.

It imposes the necessity of the protection of people and the environment in the short and long terms. It reiterates the importance of various factors such as financial and social public acceptance to be taken into consideration, as well as the requirement to keep the radiological impact of the facility As Low As Reasonably Achievable (ALARA, the principle that balances safety and technical means of ensuring it).

The Safety Guide provides guidance on requirements to waste packages, engineered and geological barriers and recommendations on the disposal facility design and layout.

2.2 Iterative Approach for the definition of R&D programmes to support the development of Cigéo project

2.2.1 The R&D Programme

The R&D program, developed for over 20 years, is a planning and integrated perspective tool to support the milestones of Cigéo project.

The R&D programme seeks to acquire the scientific and technological data k to support the concept design (including construction and operating), and the long term safety assessment, in particular in quantifying the safety margins and reducing the uncertainties if necessary. In order to guaranty a level of flexibility/adaptability between the R&D and the Cigéo project development, the R&D programme was detailed in a 4 to 5 year plan, revised yearly, and up-dated at the closure of iteration and/or at each major milestone of Cigéo project.

The R&D programme covers a wide spectrum of scientific and technological domains (earth sciences, materials science, environmental science, applied mathematics, informatics, human and social sciences, robotic etc.) as well as scientific disciplines (hydraulics, mechanics, thermal phenomena, chemistry, radiochemistry etc.). It covers the scientific and technological R&D activities in the URL by also in ground laboratories.

The R&D programme is reviewed by the scientific council of Andra and for the URL R&D programme each experiment is reviewed by a pool of experts, members of national and international research entities (academic laboratories, national and private research institutions) by introducing and pooling the efforts around integrated multi-disciplinary research topics. The programme is implemented by clusters of laboratories/partnerships and by national-projects and European or international projects.

2.2.2 The Development Project Plan

A Project Development Plan (PDP) was introduced in 1995 to coordinate all the activities related to the Cigéo project and to break down the schedule into successive research iterations in order to achieve a continuous progress toward an industrial solution. The completion of each development phase of Cigéo was confirmed, usually by a project review. During the review, the performance of the overall system was assessed by compiling the information obtained. In addition, it was evaluated how the remaining uncertainties could jeopardize the functions of the disposal. The results were reported to the evaluators and stakeholders. Then, the objectives of the following iteration were re-defined (Figure 6).

Prior to launching a new iteration, the requirements and objective of the Cigéo project could evolve as the decision-making process was clarified and refined. It was then important to have a vision on several successive iterations to reduce and mitigate the risk of a data acquisition process that would take longer than the time lapse between two project reviews.

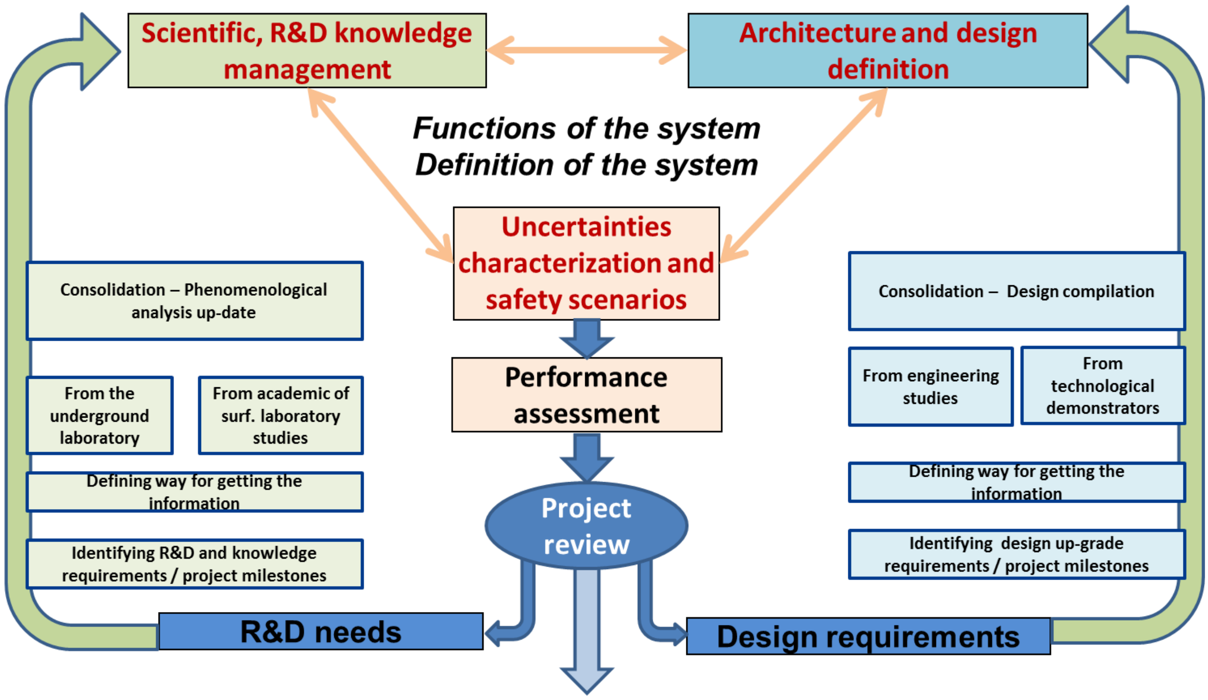

Figure 6 Scheme of the Cigéo project iteration between R&D needs and Design requirements

2.2.3 Iterations completed and in progress

To date, 7 main research iterations of Cigéo project were carried out:

1) In the framework of the 1991 Act:
   - 1996 : license application for 3 URLs;
   - 2001 : Initial design option + International Peer review (NEA);
   - 2005 : Principle demonstration of Cigéo (long term safety and operation) + International Peer Review (NEA).
2) In the framework of the 2006 Act:
   - 2009 : Operation Safety options and choice of locations for underground facility (ZIRA) and surfaces facilities;

- 2011 : Conceptual Design;
- 2015 : Basic Design + International Peer Review (IAEA).

3) In the framework of the 20016 Act:

   - 2016 : Cigéo Operation Safety options report (DOS), in preparation to licensing application to submit at a time horizon 2020.

In April 2016, Andra sent ASN the Safety Options File (DOS) for the Cigéo project. Submission of the DOS means that the project becomes part of a process governed by the regulations concerning base nuclear facilities (INB), more specifically by article 6 of the decree of 2 November 2007.

ASN examined this file. In this respect, it requested an expert assessment from its technical support organisation, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and also assessment by its Advisory Committees of Experts.

Furthermore ASN submitted the DOS report for review by experts from foreign safety regulators, coordinated by the IAEA.

Following this technical examination phase, ASN consulted the public about its draft position from 1 August to 15 September 2017. After analysis of the contributions received, ASN issued its position on January 11, 2018.

ASN, in its conclusions, considered that the Cigéo project has overall achieved sufficient technical maturity at the safety options report stage. It also considered that the safety options report is documented and substantiated and constitutes a significant step forward with respect to the previous files submitted to ASN for its opinion.

However, some topics of the safety options report need to be supplemented in view of the licencing application that Andra intends to submit at a time horizon 2020. The main supplements requested concern the justification of the underground disposal architecture, the design and sizing of the installation to withstand natural hazards, the design of bituminized sludge's disposal packages and cells to manage possible fire situation, the monitoring of disposal, and the management of post-accident situations.

The iteration in progress is Cigéo project technical design, safety case, and license application that should be submitted at a time horizon 2020.

3. Cigéo's Roadmap

3.1 The Cigéo Disposal Concept

The objective of defining long-term safety functions and attributing them to a specific component of a waste repository system is to ensure the protection of the human and the environment against the dissemination of radioactive substances over the long-term.

Figure 7 presents an overview of the Cigéo Project facilities.

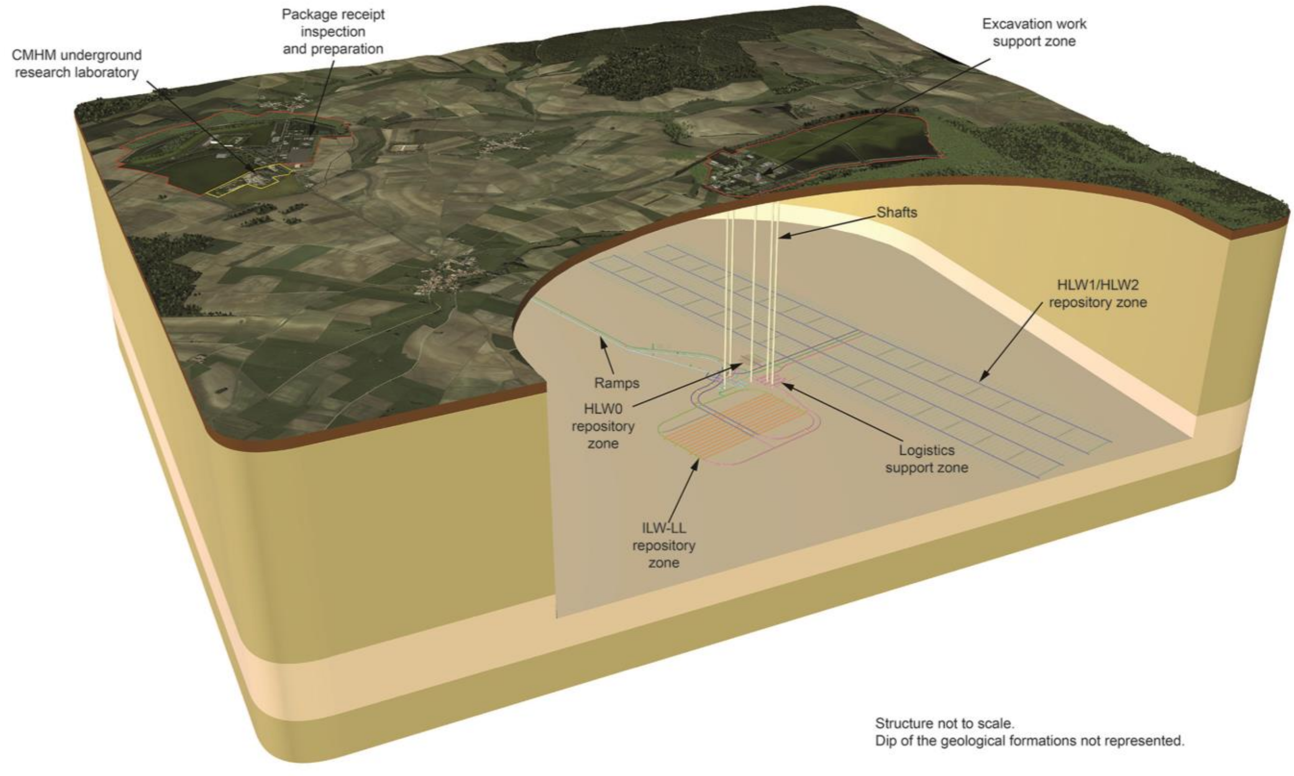

Figure 7 Overview of the Cigéo project facilities

Among the principal safety functions required from a geological repository, one can point out the waste isolation from surface erosion phenomena and human activities (i.e., making the waste virtually inaccessible through erosion to accidental intrusion by human being); and containment properties of the host rock in order to keep the radioactivity inside the repository system.

Radioactivity containment relies on the following safety functions:

- To limit/restrict/oppose water circulation as water is the main vector of radionuclide migration;
- To limit the release of toxic elements and prevent them from leaving the repository and delay their migration into the environment (for various types of waste different actions may be presumed necessary); and,
- To preserve the characteristics of the host rock (in terms of response to chemical disturbance, heat dissipation, and mechanical deformation).

These three safety functions rely primarily on the favourable characteristics of the Callovo-Oxfordian formation. Moreover, the design of Cigéo (architecture, engineered components) and its operation aim to preserve and/or to take benefit of these favourable characteristics.

Thus, the disposal design aims to make use of and enhance as far as possible the beneficial properties of the clay formation. For instance, design solutions such as a plane disposal, a location of the disposal cells access drifts at least 50 m from the upper and lower limits of the Callovo-Oxfordian, the dead-end architecture, and grouping the termination of access (shafts and ramps) in the Callovo-Oxfordian to avoid the hydraulic “U tube” effects illustrate this (Figure 8).

In order to limit disturbance in the clay host rock, technical arrangements seek to ensure appropriate dimensioning of the disposal packages, cells, and sectors, as well as control of the materials introduced into these structures. In addition, engineered components can contribute to safety functions by complementing or ensuring performance redundant with that of the clay host rock.

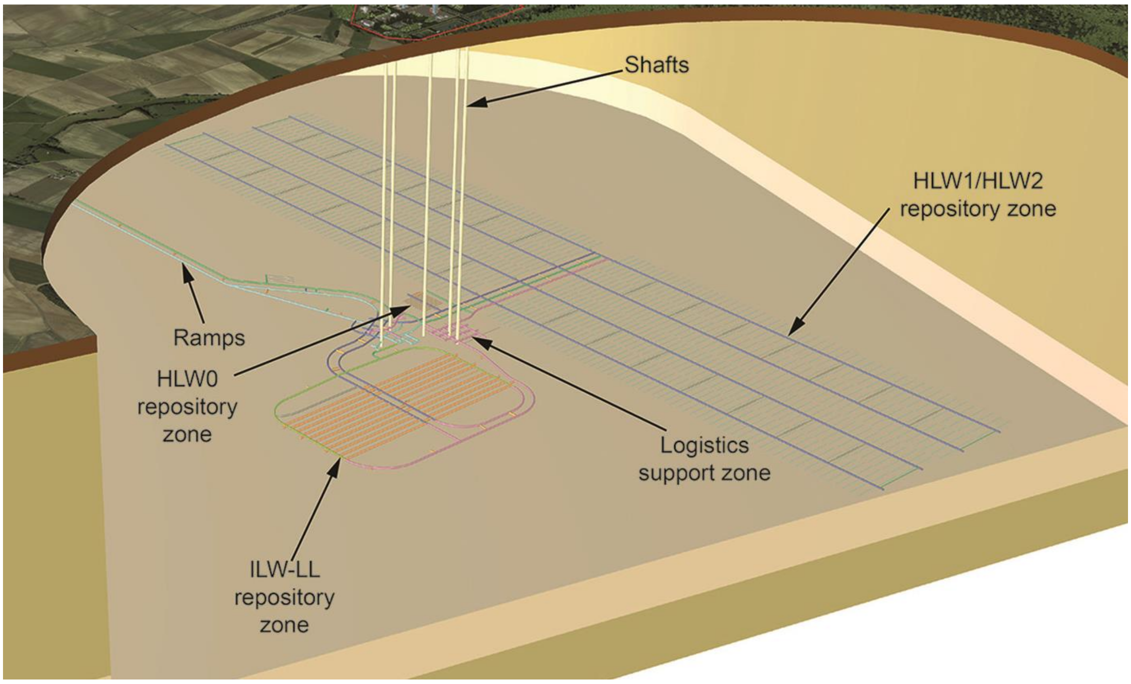

Figure 8 *Cigéo main level layout*

Nevertheless, at long term the main safety role is played by the Callovo-Oxfordian and the seals of the access (shafts and ramps).

It was considered that the characterization of the favourable properties of Callovo-Oxfordian should be performed at first, then the characterization of disturbance (thermal, mechanic, hydraulic, chemical, biological, etc.) generated by the repository would have to be investigated and modelled to assess that their impacts on the Callovo-Oxfordian for long-term safety are acceptable.

This approach was the basis of the R&D programme and thus the URL part was built to achieve this goal.

3.2 The Disposal Components

Following the safety analysis and in particular the requirements for the long term safety, the strategy for R&D research, including URL activities aiming at providing technical design options for Cigéo was built taking into account the six following main components:

- General geological features;
- High Level Waste (HLW) components;
- Intermediate Level - Long Lived waste (ILLW) components;
- Connecting and closure structures (ramps, shafts and drifts);
- Full-scale repository comprising the layout of the underground infrastructures; this includes the knowledge of the geological settings as well as the development of numerical simulation related to their evolution.

In addition, environmental monitoring, observation/surveillance and human and social sciences is considered as a component but will not be presented here.

Safety functions that should be achieved during the lifetime of the disposal are divided in 2 main domains:

- Safety functions for operation;
- Safety functions for post-closure.

Requirement for the potential retrievability of waste packages during operation were added.

Each of the experiments carried out in the French URL is linked with the analysis of safety functions and translated into R&D needs. These R&D needs will be presented hereafter and the full list of experiments will be presented in section 5.

Actually, some of the experiments carried out in the URL are specific to a component but several of them such as drift excavation survey, damaged zone survey, pore water composition or permeability measurement are embedded as a subset in a component experiment.

3.2.1 General Geological Features

Main scientific and technical R&D topics

This component comprises the features that are related to the geological environment in its natural state. This includes the Callovo-Oxfordian as the host rock, but also the surrounding geological formations that are participating to the migration of radionuclides that could reach the limits of the Callovo-Oxfordian to the biosphere (Figure 2). The knowledge was acquired during the drilling phases prior and during the construction of the URL, and will be completed during the construction of the repository through additional scientific drillings.

The monitoring network around the future Cigéo disposal comprising a regional seismic survey and a piezometric survey in all surrounding geological formations will also provide additional information.

3.2.2 HLW Component

Main scientific and technical R&D topics

HLW disposal packages will be disposed of in micro-tunnels that are about 70 centimetres (cm) in diameter and about a 100 to 150 metres long. A metallic sleeve allow to emplace the disposal packages and their possible retrievability by a pusher robot (Figure 9).A cementitious-swelling clay based material is filling the gap between the sleeve and the host rock.

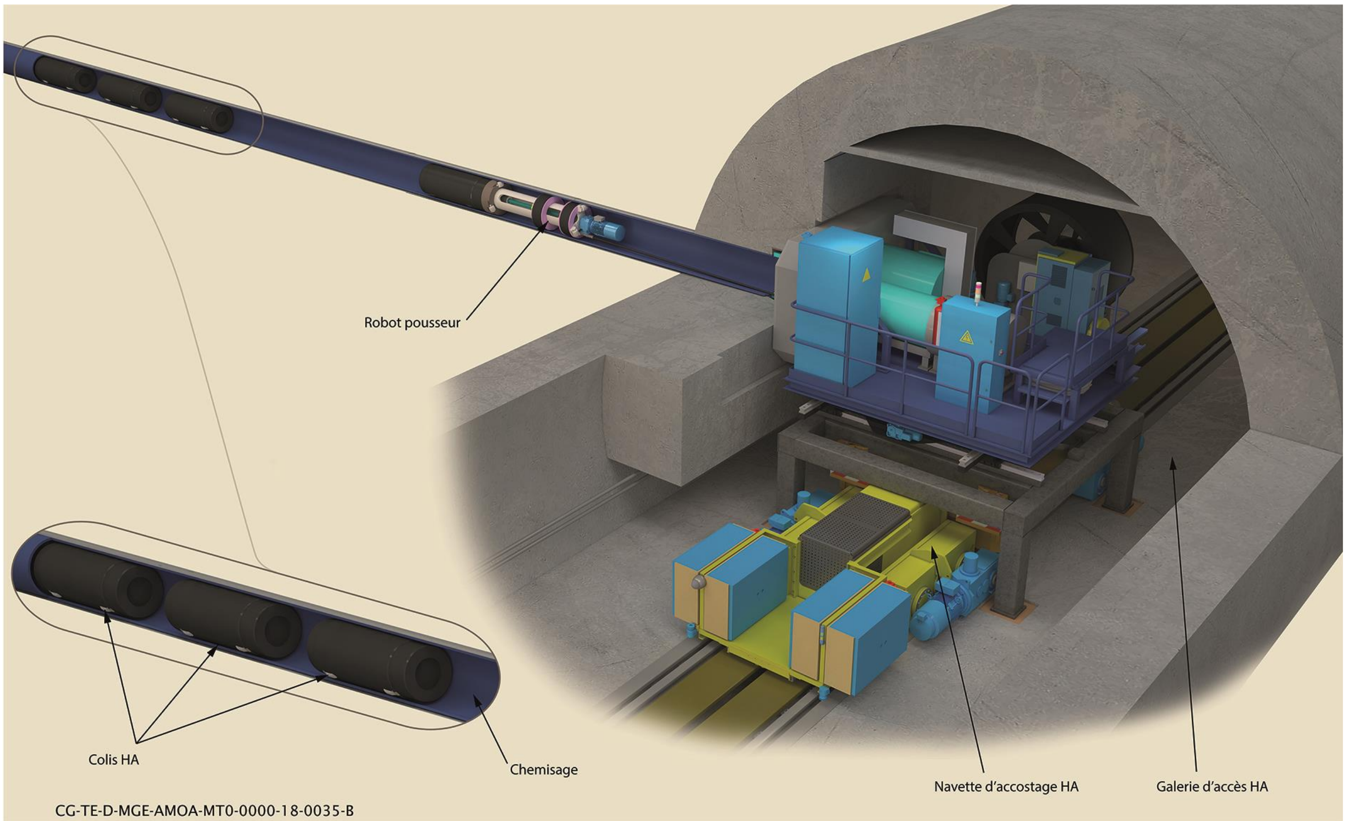

Figure 9 Scheme of HLW disposal Cell and pusher robot to emplace the disposal packages

For the HLW disposal sector a robust and reasonable thermal dimensioning should be assessed, taking into account the THM behaviour of clay rock and the safety requirements for temperature at the limit of the host rock formation.

For the HLW disposal cell, the robustness of the concept, i.e., meeting requirements and construction, has to be demonstrated. It includes the precise dimensioning of the HLW disposal cell and its components: disposal containers, spacing buffers, sleeves, and filling material.

In this context, the main scientific topics to be addressed are:

- The mechanical behaviour of the clay rock (damaged zone);
- The fracturing (under gas and/or thermal loading);
- The corrosion and mechanical strength of the sleeve and the over-packs;
- The physico-chemical behaviour of the filling material.

Technical experiments will be dedicated to development and optimisation of the construction disposal cell such as (i) the drilling technic, (ii) the length of the disposal cell up to 150 m, and (iii) the emplacement of the filling material around the sleeve.

In parallel, ground surface studies should consolidate the HLW source terms for the safety assessments, taking better account of the environment (including the filling material) in the glass matrix behaviour models.

Other scientific issues are also considered for they could lead to optimize the concept. For instance, for the geological medium, the post-closure safety should be improved by relaxing the thermal criterion from 50°C up to 70°C for arrival of water on glass and radionuclide release.

3.2.3 IL-LLW Components

Main R&D challenges and related scientific and technical topics

IL-LLW packages will be disposed of in tunnels (drifts) of several hundred metres long and around 10 metres in diameter (Figure 10). They will be stacked one on top of another, in layers, by a stacking crane.

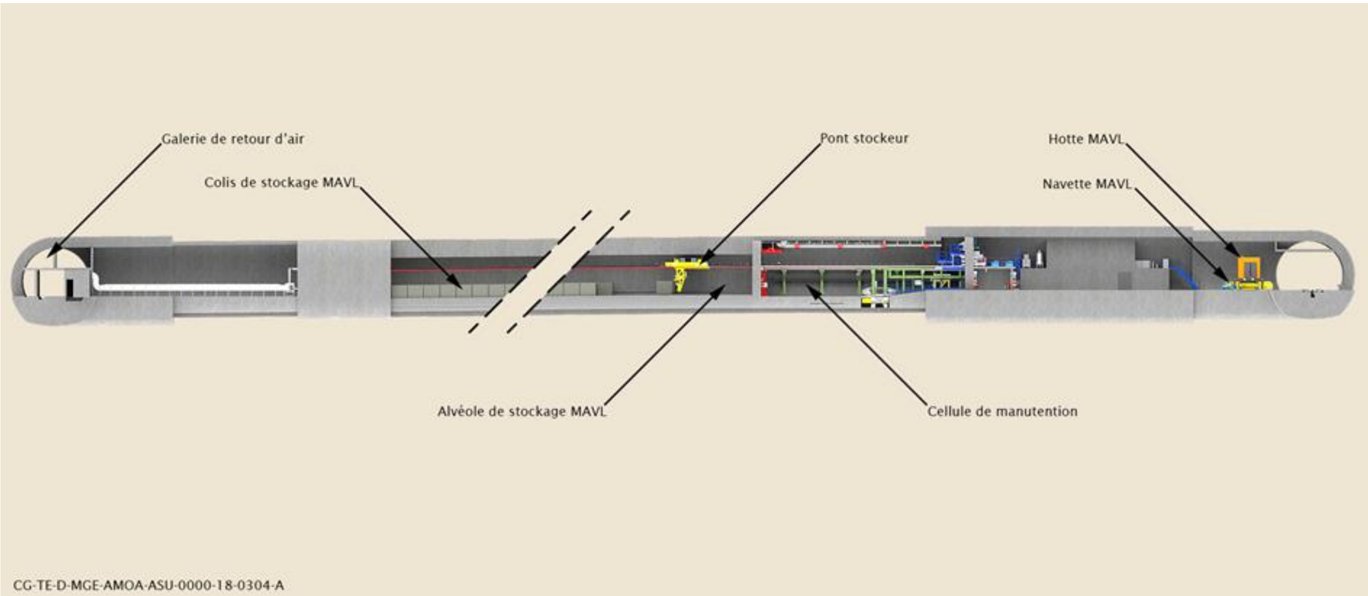

Figure 10 Scheme of IL-LLW disposal Cell concept

For IL-LLW disposal cells, the RD&D primarily focus on the dimensioning (including spacing) and construction feasibility of structures of large diameter. The bulk of the studies and experiments is concerned with the mechanical behaviour of the structures. The experiments are oriented towards the characterisation and modelling of the near field damaged clay rock zone (initial, time-dependent) on drift walls or front face.

In order to guarantee the stability of the disposal cells during operation, the time-dependent mechanical behaviour of the cement-based materials and the chemo-mechanical durability of the cement aggregates are tested in lab and in-situ experiments.

Innovative construction techniques such as compressible support segments have been tested during tunnel boring in the URL to accommodate large-diameter disposal cell prototype to be built at the underground laboratory (section 65 m^2) during the industrial pilot phase (up to section 85 m^2).

In addition, for IL-LLW disposal cells the experiments will aim at assessing the possibility of co-disposal some IL-LLW. It will consist of defining the spacing between disposal cells.

The behaviour of the radionuclides and toxic chemical substances in the IL-LLW disposal cells and the near-field clay rock will be tested through experiments on actinides and experiments on impact of the complexing compounds and salts on the migration of radionuclides. Migration of gaseous radionuclides in unsaturated conditions for IL-LLW packages is also part of the R&D programme.

3.2.4 Closure Structures (seals and backfill)

Main scientific and technical R&D topics

The construction feasibility and demonstration of long-term performance of the seals (access and drift) should be demonstrated. The performance is linked to the behaviour of damaged clay rock at the location of the seals. Figure 11 presents a basic seal structure.

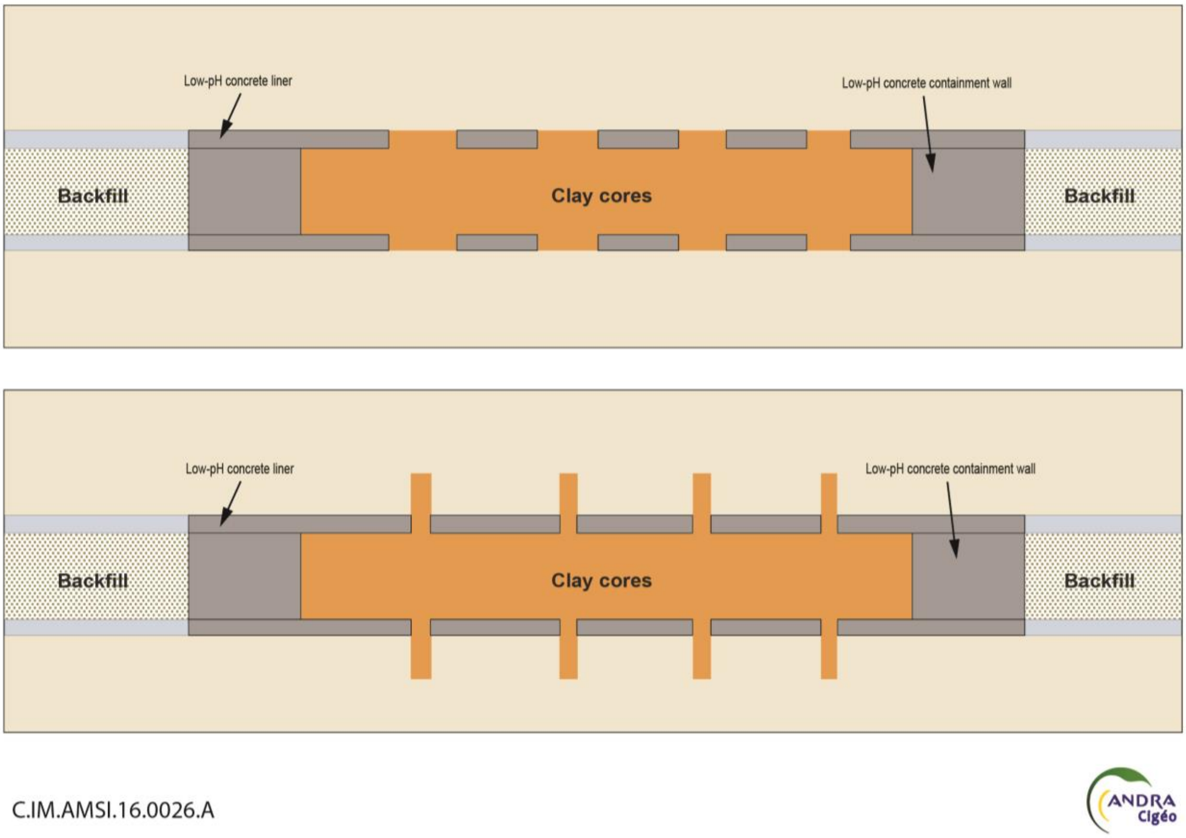

Figure 11 Scheme of a drift seal with removal of part of the concrete support with and without key

For the shaft and access ramps seals, specific studies are carried out for that there are implemented in the upper part of the Callovo-Oxfordian (e.g. silty carbonated unit). It should be checked that according to high mechanical properties no continuous fracturing is occurring in the clay near filed in the silty-carbonated unit that favourites the limitation of water flow, and thus radionuclide migration by the underground facilities to the upper surrounding geological formations..

Of particular importance are the studies on the self-sealing capacity of the damaged clay rock in the Callovo-Oxfordian clay unit (major part of the clay formation – location of the underground facilities). In addition, the behaviour of the swelling clay cores and the fitting with the requirement towards the HM-gas transfer is studied.

Other topics such as behaviour of the concrete containment walls and linings, chemical degradation of the low-pH concretes, and chemical interactions between low-pH concretes/clays and impact on swelling pressure should be fully understood.

Experiments in the URL started in 2005 by testing the feasibility of slots filled with bentonite. Many other experiments representing a part of the slot have been carried out since them. However, most of these properties at large scale will only be experimented during the pilot phase of the disposal construction.

3.2.5 The Full Scale Repository

Main scientific and technical R&D topics

The studies related to the component “full scale repository” aim at acquiring - within the disposal footprint - the best characterisation of the thermo-hydro mechanical (THM) parameters are conditioning the operating and post-closure safety.

In parallel, the methodology and the tools relating to monitoring have to be defined.

This R&D domain is mainly treated through desk studies and modelling of the phenomenological representation of the Thermo-Hydro-Mechanical and Chemical (THMCR) behaviour of the repository with the following aspects:

- Representation of water flows within the disposal in the future million years after full water saturation of disposal;
- Assessment of the thermal load;
- Assessment of the TH-Gas behaviour transient phase of the repository and Callovo-Oxfordian;
- Assessment of the mechanical behaviour of the repository and the surrounding geological medium, including the TH couplings;
- Assessment of the chemical evolution of the repository and the impact on near field Callovo-Oxfordian;
- Assessment of radionuclide release and migration (in gaseous and solute forms) within and from disposal to biosphere during future million years.

This aspect of the R&D programme implies the use and development of high-performance calculation methods.

4. Development Stages of the URL - R&D Activities

Since its inception, the overall objectives of the URL have been:

- To facilitate direct access to the potential host medium in order to assess its contribution to the disposal concept (i.e. to confirm its containment properties, to confirm the constructability of a repository at an appropriate depth to provide isolation from the biosphere); and,
- To define with more certainty the layout of the repository and to provide information and data for safety evaluations throughout the project phases.

For Andra, the design of the URL took more than 4 years. One of the key elements was to take stock of the work carried out in other foreign programmes. Firstly, the extensive investigation programme carried out prior to the project, the Aspö URL construction (Sweden), was thoroughly studied and adapted to a sedimentary context. Furthermore, the knowledge coming from existing "methodological" or generic URL (Switzerland, Belgium, and France) helped to set up of the first experiments in the URL on the Meuse/Haute Marne site.

Another important point was to integrate into the design and the experimental program requirements from some stakeholders, including the commitment that the URL should never be a part of or a precursor of the repository. These requirements had a direct impact on the design of the URL, its construction, and its later operation. For instance, the diameter and the equipment of the shafts were limited to ensure that they would never be converted for the transfer and disposal of radioactive waste.

The following paragraphs describe the main steps of the URL's R&D programme during its construction and operation. The evolution of the URL's R&D programme over time is illustrated by selected experiments.

4.1 Scientific and Technical Objectives of the URL - Construction License Preparation (1992-1996)

The first URL's R&D programme after the 1991 planning act was oriented towards the demonstration of the technological feasibility of underground structures (shafts, drifts) and the containment properties of the clay host rock.

In order to achieve this goal, excavation machines, supports, and loadings were designed. In addition, experiments to characterize the clay host rock's response with time were prepared to evaluate near and far field mechanical damage and evolution. These evolutions are linked to excavation methods and support types.

The basic design of the URL, as presented in the construction license application, considered two 500 m deep shafts providing an access from the surface to the claystone host rock.

The main shaft has a 5 m diameter and allows access for personnel and equipment, material extraction, and ventilation. The 4 m auxiliary shaft located 100 m away from the main shaft accommodates the ventilation system and ensures the mining safety, and it is also a second access for taking down equipment.

From the shafts, the laboratory has two levels of access drifts at depths of -445 and -490 m respectively. The upper drift will have a simple T-shaped configuration and a total length of about 4 m. It provides access to boreholes in order to monitor shaft-sinking effects through the claystone host rock ("mine y test").

The drifts at the 490 m level constitute the key experimental level of the laboratory. Experimental zones were located aside the rectangular layout (circulation and ventilation loops) in a specific area in order to allow construction and drift-fitting work to take place at the same time.

4.2 Drilling Investigation Phase (1993-2000)

The main objective of the preliminary investigation phase was to verify the existence and characteristics of the host formation and the parameters of the over and underlying rocks, particularly the hydrogeological parameters of the Oxfordian and Dogger formations.

Particular emphasis was placed on taking samples from the Callovo-Oxfordian shales formation to specify its chemical and mechanical characteristics.

The work performed during this period was relatively conventional, using sedimentary prospection tools (surface mapping, seismic geophysics, borehole drilling, and analyses of drill cores) and relying as much as possible on former work performed in the field of oil prospection. Nevertheless, from the outset, specific techniques for geochemical monitoring of boreholes and hydrogeological testing in very low permeability formations were implemented.

Preliminary research in the sector identified involved:

- Detailed surface geological surveys;
- Deep borehole drillings (HTM102, MSE101; (see Figure 3);
- 2D seismic profiles;
- Systematic and exhaustive search for data acquired from previous geological surveys and borehole drilling operations carried out in the sector.

Results for the period 1993 to 2000

The geological survey carried out during this period led to the qualification of a site for an underground laboratory with the following characteristics:

- Simple geometry of the Callovo-Oxfordian layer characterized by its large extent, its continuity and horizontal layering;
- Very low permeability of the Callovo-Oxfordian and absence of aquifer on either side of this clay formation, both favourable characteristics from a hydrogeological perspective;
- Possibility of digging drifts and installing conventional supports without major difficulties;
- Geochemical properties of the Callovo-Oxfordian favourable to radionuclide retention (40 to 45% of clay mineral with 10 to 20% of illite, about 30% of R0-R1 mixed layer mineral and a low percentage of chlorite and kaolinite);
- Absence of seismicity and a stable geodynamic context ensuring the stability of the geological and hydrogeological conditions over a long period of time (millions of years);
- Callovo-Oxfordian clay layer at a sufficient depth (>400 m), and absence of natural resources of obvious interest above or near the proposed site.

Figure 12 presents the location of deep boreholes drilled during the first drilling survey phase (1993-1996). Results from these studies complemented the existing data.

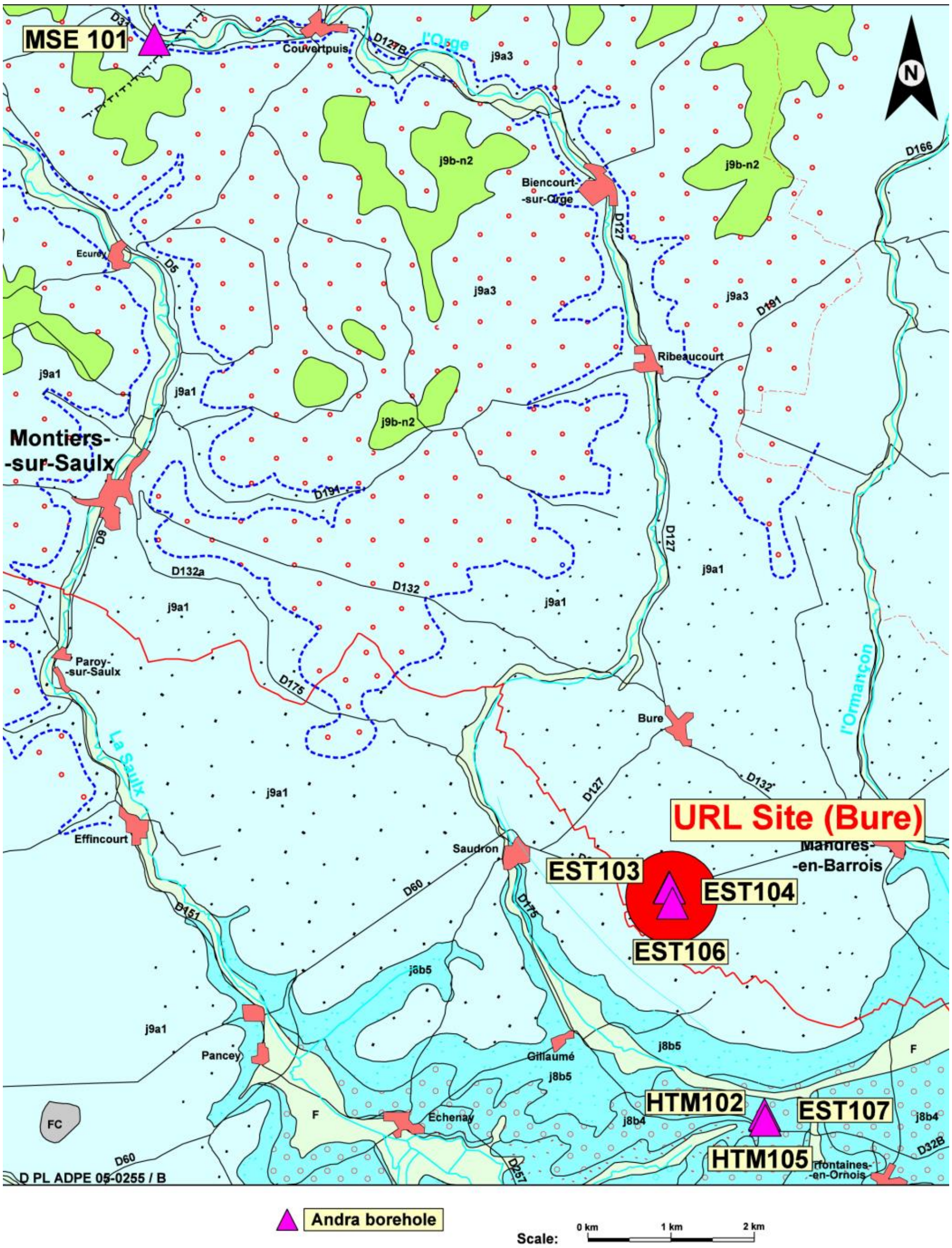

Figure 12 *Location of deep boreholes drilled during the first drilling survey phase (1993-1996)*

4.3 Activity in the URL 2000-2006: the Dossier 2005

4.3.1 URL Construction and Operation

4.3.1.1 The R&D Plan for URL

The R&D plan intended to fulfil the expectation of the 2005 milestone leading to the 2006 Planning Act.

The objectives of the URL for the 2000-2006 years were mainly the *in-situ* characterization of the physical and chemical properties of this rock. This involved achieving a level of knowledge that may be used to develop disposal conceptual designs and perform preliminary safety studies. The results should make it possible to assess the safety of a disposal over several tens of thousands and even hundreds of thousands of years.

Figure 13 presents the layout of the URL and the experimental zones with boreholes in operation between 2000 and 2006.

In line with the safety guides, the first R&D plan was focused on three of the major functions of the repository:

a) Containment capability of the clay host formation

   This containment capability comes from the specific physical characteristics of the clay host rock and the physico-chemical characteristics of the interstitial fluids and their interaction with the solids. The fundamental physical characteristic is permeability. This property is studied through various specific tests.

   The chemical characteristics of the interstitial fluids condition the mobility of the various radionuclides likely to be found in the natural environment. The studies focus on knowledge of the geochemistry of the interstitial fluids in equilibrium with the minerals in the rock and on the diffusion and radionuclide retention capabilities (See PAC Experiment).

b) Creation of mechanical damaged and disturbed zones associated with drift excavation

   The main purpose of the studies on this topic is to investigate how the clay host rock reacts to the excavation of shafts and drifts and the associated development of the damaged and disturbed zone. Several techniques and methodologies used at Bure URL had been previously developed at Mont Terri Rock laboratory. Damaged zone (EDZ) and disturbed (EdZ) were characterized during monitoring of the shaft and excavation of the experimental drift at 445 m (See REP experiment).

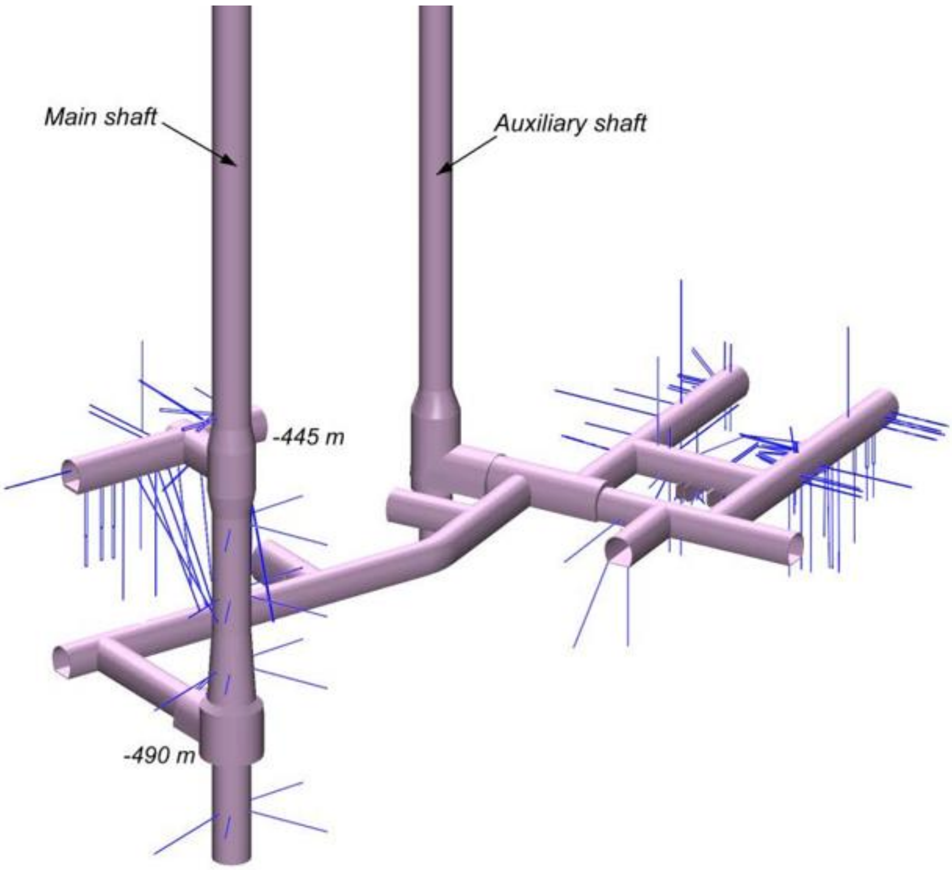

Figure 13 *Scheme of URL construction and experimental zones with boreholes in operation between 2000 and 2006*

c) Assessment of sealing zone concept

- The sealing of a drift is a major issue when considering the disposal construction options. It requires the design systems to re-establish a low water permeability near close that of the clay host rock by overcoming potentially negative effects from the damaged zone surrounding the drifts and shafts. The system studied for the Cigéo project is called “anchor key.” An anchor key is a slot (e.g. cut-off) of several meters long and around 20 cm thickness excavated perpendicularly to surface of the drift and filled with swelling clay (bentonite).
- The slot filled with swelling clay is supposed to interrupt a potential flow along the drift in the damaged zone. Experiments on the feasibility of an anchor key were conducted, first in the Mont Terri Rock Laboratory and subsequently in the KEY drift at the main level of the Bure URL.

4.3.1.2 Shaft-Sinking Method

The choice of a suitable shaft-sinking method was limited to drilling and blasting. This approach was chosen over other shaft-drilling methods due to the lack of experience with shafts as large as those of the laboratory. With a view to save time, raise-boring was ruled out because both shafts were sunk in parallel from the surface. The most important consideration, however, was the need to conduct scientific activities and observations in the shaft during construction which would have been very difficult in a shaft-drilling operation. The selected shaft-sinking method uses a multistage platform which supports all shaft-construction operations, including drilling and blasting, mucking, and applying the concrete liner.

The support system was installed directly and immediately after excavation. It consists of bolts and wire mesh covered with shotcrete in order to prevent spalling. The final lining consists of concrete poured in 3 m sections at a time. The thickness of the concrete ring is approximately 30 and 45 cm in carbonates and argillaceous rock, respectively. In addition, the stress within that lining is recorded by vibrating wires that are fitted while pouring the concrete ring.

4.3.1.3 Drift-Opening Methods

Due to the building requirements of the Bure URL, the drill-and-blast method was applied at a depth of 445 m and the pneumatic-hammer method to open drifts at a depth of 490 m. Supports consist of 2.4 m bolts and sliding arches. Down at 490 m, the floor is reinforced with bolts. A shotcrete lining sprayed over wire mesh prevents spalling. Since one of the purposes of geo-mechanical measurements is to assess potential convergences and stresses on a final lining, specific zones have been equipped with sensors for convergence measurements and measurements on supports. The observed convergences depend on the orientation of the drifts compared to main horizontal in situ stress and on the excavation and support methods being used.

4.3.2 Follow-Up Construction of the URL: Drainage of the Shafts (2000-2006)

Since the shafts giving way to the underground facilities were expected to drain all terrains, the impact of this drainage on the Kimmeridgian marls and Oxfordian limestone was monitored. In March 2000, disturbance-monitoring boreholes, for hydrogeological and geochemical purposes, were air drilled using an inverse circulation method that minimizes contamination from drilling fluids.

To monitor the Oxfordian formation, two 420 m deep boreholes were drilled (Figure 14) (EST 201 and EST 203) and equipped with five measuring chambers, thereby supplementing boreholes EST103 and EST104 located north of the laboratory site.

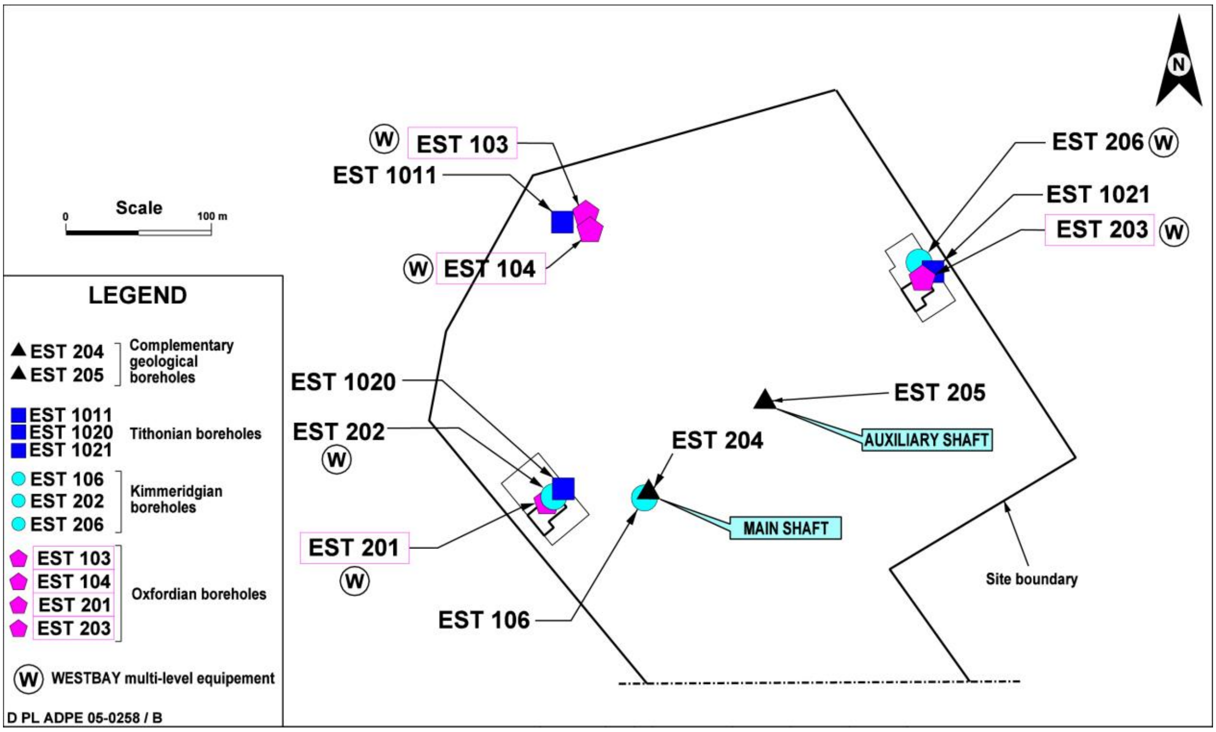

Figure 14 Location of shaft drawdown monitoring boreholes

Investigations on the laboratory site prior to the sinking of two shafts started in November 1999. The sinking of the shafts started in September 2000

In 2001, before the main shaft sinking work reached the production horizon of the Oxfordian formation, borehole EST103, equipped with a piezometer since 1996, was re-equipped with an innovative set of gauges. An absolute pressure gauge was installed in the Callovo-Oxfordian age formation to measure the pressure inside the shales for at least 7 years. This gauge, called "EPG," for Electromagnetic Pressure Gauge, was derived from the oil drilling technology.

The most significant feature of this gauge is the wireless transmission of signals using low frequency transmitters. By eliminating the need for wires, the gauge can be isolated in the borehole using low-permeability cement with a minimal volume of water surrounding the instrument. A multipacker completion was also installed in the base levels of the Oxfordian formation to monitor the heads at the interface with the host formation.

The excavation of the Oxfordian limestone started on 11 November 2001 in the main shaft and 29 March 2002 in the auxiliary shaft. The excavation lasted 909 days in the main shaft and 748 days in the auxiliary shaft. Overall outflow measured just after the excavation of the Oxfordian limestone was 9.7 l/min in the main shaft and 8.4 L/min in the auxiliary shaft.

Pressure monitoring in borehole EST201 provides a good example of hydraulic interference between shafts and monitoring boreholes. Figure 15 shows penetration versus time for the upper part the main shaft, with porous levels represented by blue and black vertical bars corresponding to the depth and time the boreholes were drilled during shaft sinking. The hydraulic head versus time is shown in the lower part of this figure.

The first interference was observed when borehole PPA0012 was drilled across the upper porous level Hp7. Drawdown was observed in the two upper intervals (corresponding to Hp7 and Hp6) in borehole EST201, starting simultaneously on 26 November 26 2001. These observations indicate that porous levels Hp7 and Hp6 are hydraulically connected. During geological mapping in the main shaft, a vertical fracture from Hp7 to Hp6 was observed on the wall and this may explain the observed vertical connectivity.

These two porous levels were also affected when Hp7 and Hp6 were excavated in the main shaft and when a cover drilling (PPA014) crossed Hp6. Further excavations in the main shaft have had no effect but some effects observed later could be related to the auxiliary shaft excavation.

For interval three corresponding to porous level Hp5, no interference was observed until a cover drilling (PPA0015) crossed Hp5 in the main shaft, indicating that this porous level is isolated hydraulically from the two upper ones. Simultaneously, a slight decrease of hydraulic head for the two deeper intervals in EST201 was observed, corresponding to porous levels Hp1 to Hp4, indicating that there is a low hydraulic connectivity between Hp5 and the four deeper porous levels.

Further observation of pressures in borehole EST201 confirms that:

- Hp7 and Hp6 are highly connected hydraulically with each other but not connected to other porous levels;
- Hp5 reacts on its own with a low connection to the four deeper porous levels; and,
- Hp1 to Hp4 represent the third group of hydraulic response and are connected.

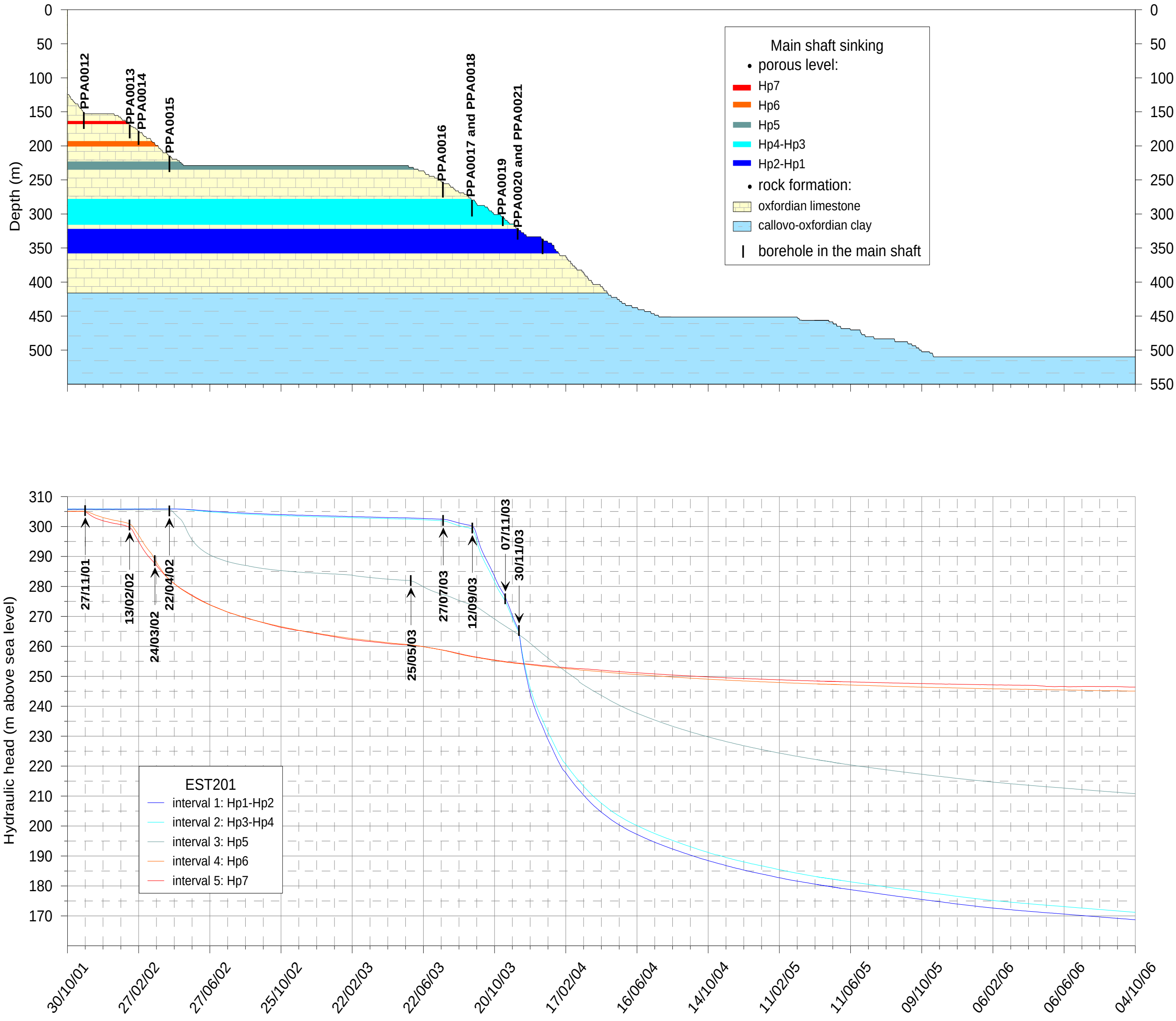

Figure 15 *Shaft sinking and hydraulic head measurements in borehole EST201*

4.3.3 Designing and Preparing Experiments

The design of an experiment therefore requires an initial expression of needs in the form of the clearest and most accurate objectives possible while remaining realistic as to the feasibility of such an experiment and to the resources that can be mobilized. Three more stages follow; they are necessary to design the experimental work, i.e., to convert an idea or a concept into a work and scientific measurement programme which meets the scientific objectives listed in the research project:

- The first stage was drafting the expression of needs;
- The second stage involved a detailed specification of needs that can progress in several steps, depending on the complexity of the project; and,
- The third stage was the production of scope of work and technical specification of the requirement that details the work to be carried out, its sequence under an operational schedule and related organizational and monitoring provisions.

Contractual preparation is a fundamental stage. For a public body such as Andra, the consultation procedures had to conform to public procurement rules.

The selection of the contractors has considerable influence on how the organization and monitoring systems are set up. This selection is most of the time based on a compromise between the need to consider the core expertise of each enterprise, the auxiliary services it may provide by juggling with internal synergies, and its actual capabilities in terms of mobilization of internal and external resources around the project.

For an operation like the URL at Bure, 60 contracts were generated; two-thirds as calls for tenders open to European competition and the rest as partnerships with French and international organizations.

4.3.4 REP Experiment: Rock Mass response to Shaft Excavation

A large part of instrumentation and measurements taken in boreholes from the drift at 445 m were intended to be used to assess the hydro mechanical disturbance generated by shaft sinking. Three sets of parameters have been monitored (Figure 16):

- Variation in interstitial pressure at the working face of the shaft progresses and the evolution of the pressure over time once the face has passed the monitoring point;
- Variation in the rock's mechanical properties as a function of time in the parts of the rock mass affected by the shaft sinking; and,
- Evolution of permeability over time in the zone influenced by the shaft sinking.

Four phases are distinguished as for the measurements and experimental work:

Phase 1: Equipment installation

The first operation after the drift excavation was the drilling of boreholes to install the interstitial pressure measurement probes. Given the low permeability of the rock, the measured interstitial pressure is expected to increase from one bar (after drilling) to reach a value close to the hydrostatic equilibrium.

Next came the borehole drilling and installation of geotechnical instrumentation (extensometer, inclinometer, deformation measurement by specific cells) to monitor the shaft sinking,

Finally, a measurement campaign of initial properties of the rock mass prior to the shaft excavation (P wave velocity, permeability, in situ deformability) obtained from boreholes through micro seismic logging, hydrogeological testing and dilatometry measurements was carried out.

Phase 2: Sinking monitoring

This phase was led to monitor the changes in physical parameters (deformation, displacement, pore pressure, P wave velocity)

Phase 3: Return to the drift following the shaft sinking completion

This measurement campaign aimed at targeting properties of the rock mass after shaft excavation (P wave velocity, permeability, in-situ deformability).

Phase 4: During the remainder of the underground laboratory operation

Long term monitoring confirmed the time-dependent hydro-geomechanical parameters of the rock in the shaft environment. Most of this equipment is still in operation.

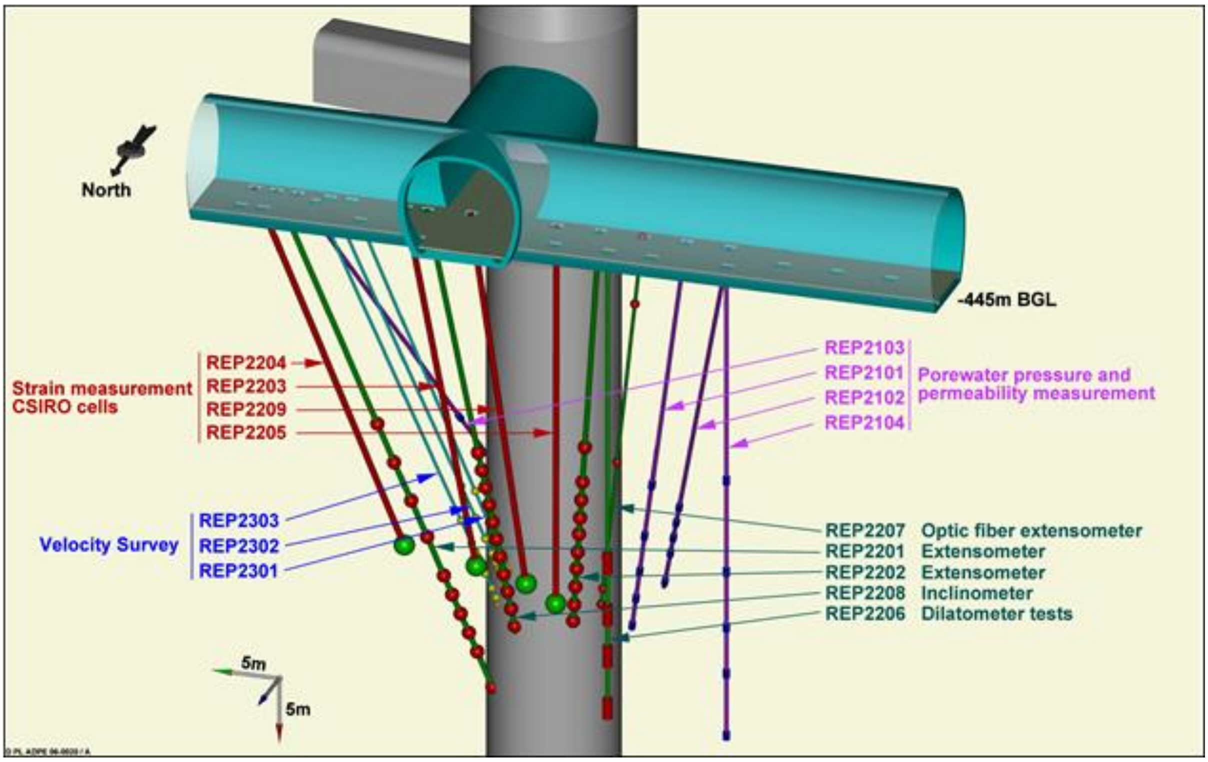

Figure 16 REP experimental setup – Following up rock mass reaction to shaft sinking

Changes in the hydraulic characteristics of the formation

Four boreholes (REP2101, REP2102, REP2103, and REP2104) are dedicated to measuring the interstitial pressure. For 3 of them, the measurement points are located around the shaft at distances of between 1.3 m and 5.2 m from the shaft wall and with orientations close to those of the minimum and maximum horizontal stresses.

The hydraulic conductivity was measured at 5 locations in each of these boreholes. The fourth borehole (REP2104) serves as a reference, given its location at 13 meters from the shaft wall. Although the hydraulic pressure was affected by the sinking of the shaft and drifts at 490 m, no modification in permeability was noted in the measuring chambers.

Monitoring the mechanical behaviour of the rock mass

Two boreholes (REP2201, REP2202) have been fitted with multi-point extensometers to measure rock displacements along the borehole axis. These boreholes are oriented parallel to the orientation of the maximum horizontal stress. An additional borehole (REP2207) has been drilled to test optic fibre displacement sensors. A borehole (REP2208) has been equipped to measure transverse displacements with respect to a borehole axis. This device is a torpedo-type inclinometer.

Deformation measurement gauges have been installed in 4 boreholes (REP2204, REP2203, REP2209, and REP2205). These CSIRO cell flexible inclusions were used to monitor the changes in the deformation field during shaft sinking and the time-dependent deformation caused by the long-term behaviour of the clays.

Deformability measurements

One borehole (REP2206) was used for dilatometry measurements before the resumption of the shaft sinking.

Measurements of variation in the propagation speed of seismic waves - velocity survey

Changes in the seismic wave propagation velocity were measured during the sinking of the shaft, constantly, in three boreholes (REP2301, REP2302 and REP2303). The three boreholes are fitted each with a system of 6 to 9 sensors acting as both emitter and receiver.

All the sensors emit signals sequentially with the other sensors in the system. The wave propagation velocity in the domain investigated by the system is established by analysing these signals. Measurements were taken before and during all the shaft-sinking stages to characterize the changes in velocity caused by the sinking.

A decrease in P wave velocity was noted during the sinking of the shaft showing a decrease in density of the rock formation. However, this drop in density remains very low (under 2%).

Thus, the organization and means implemented made it possible to follow in real time the evolution of the geomechanical parameters while carrying on construction activities in the shaft and drift. The information collected was also used to adapt devices (length of the extensometers, parameters for the acquisition of the velocity surveys) also used at a later stage at 490 m depth.

4.3.5 PAC Experiment: Determination of Chemical Composition of the Interstitial Water in the Drift at 445 m

The aim of this experiment is to determine the chemical and isotopic composition of interstitial fluids in their natural, initial state. For designing this experiment, measurements were made on solid core samples taken for pore water extraction and analyses and tests required for modelling water rock equilibriums. The experimental concept is based on feedback from other laboratories.

Experimental devices meeting the same objectives as this experiment have been tested at Mont Terri. These tests have shown the technical feasibility and efficiency of the devices. They have also revealed problems in obtaining two fundamental characteristics of the interstitial water: the carbon system state and the Redox state.

Boreholes and experimental concept

Two boreholes were drilled and equipped to characterize the upper and lower environment of the drift 445 m. The instrumentation of these boreholes and their layout are shown on the Figure 17.

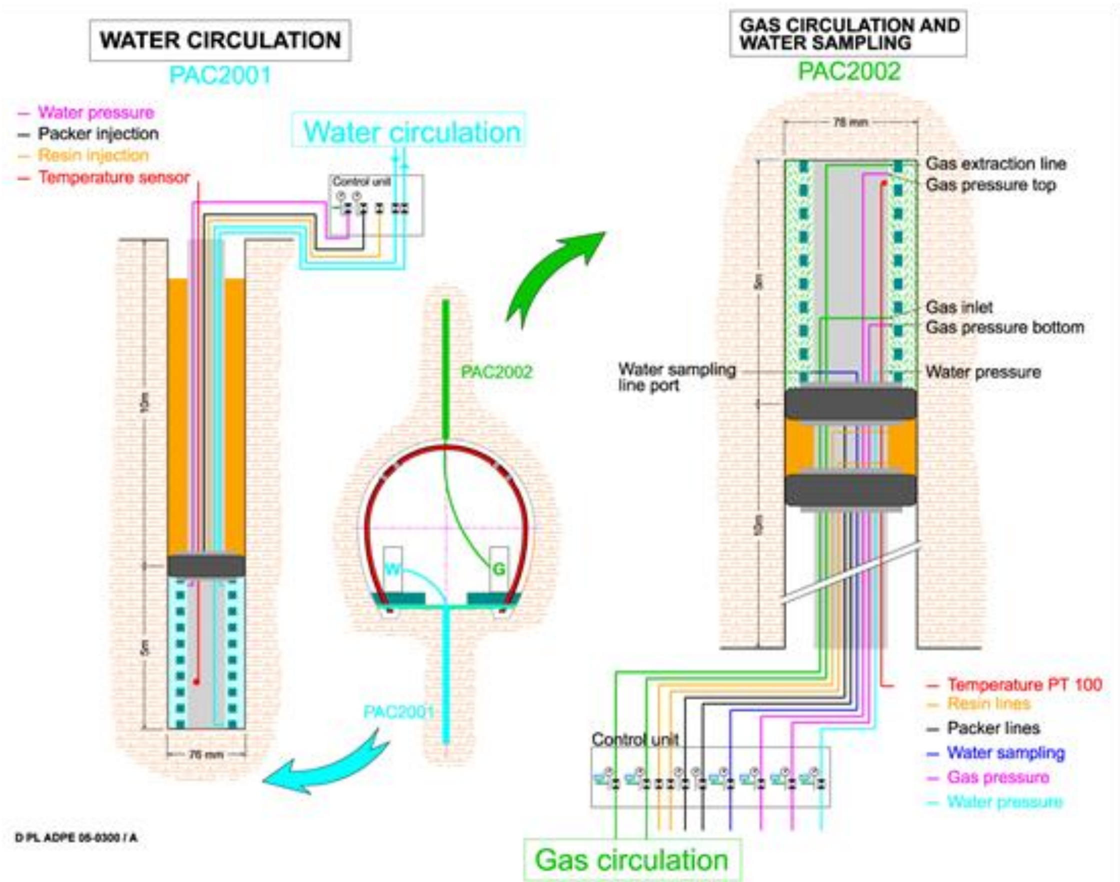

Figure 17 *Conceptual design of the chemical and isotopic composition of interstitial fluids experiment*

The PAC2001 (left side) device is designed to circulate synthetic water in the borehole section opening on the rock (test interval). The experimental concept relies on a vertical borehole drilled with nitrogen to avoid oxidization of the sulphides present in claystone rock. The 5 meter long measuring chamber (test interval) was placed about 10 meters above the ground of the drift to avoid significant disturbances. The measuring chamber is equipped with a porous filter to ensure its integrity during the entire experiment.

It is separated from the upper part of the borehole by a seal over which resin had been injected to ensure complete insulation from water and gas. Besides the resin and measurement injection lines (pressure and temperature of the chamber), the device consists of two circulation lines (injection and extraction) connected to a set of on line measurement cells (pH, Eh, electrical conductivity) and sampling cells.

The experiment started in January 2005 with the injection in the circulation circuit of synthetic water with a composition assumed to be close but slightly different to the interstitial water which a best estimate composition was obtained by modelling. The evolution of the chemical composition of the water in the circuit is monitored by pH, Eh, and electrical conductivity sensors, but mostly through water sampling at regular intervals with cells sent to specialized laboratories for analysing major ions.

The results were used to analyse the composition regarding major ions and the water/rock interaction mechanisms that govern the composition of the interstitial water.

The PAC2002 device is designed for gas equilibration and direct sampling of the interstitial water that flow in the open section of the borehole (test interval). The experimental device consists of a vertical ascending borehole with a 5 m long test interval at its far end. This equipment has been tested in the Mont Terri laboratory since 2004. In order to avoid the oxidization of sulphides present in argillaceous rock, the borehole was also drilled with nitrogen. In addition, great care was taken to restrict the development of microbiologic activity induced by the excavation and the introduction of nutrients associated with the equipment.

Two seals insulated the test interval with resin injected in between. Besides various technical lines for the injection of resin and the monitoring of pressure in the test interval, the equipment consisted of two lines for the circulation of gas in order to inject gas of a known composition and to monitor its concentration online. The equipment also included a line to sample formation water.

In this borehole, a series of gas circulation cycles has been carried out to obtain information on the dissolved gases in the interstitial water in the rock, particularly the state of the carbon system. The underlying principle of this part of the test is that the dissolved gases in the interstitial water in the rock are going to become chemically balanced with the gas circulating in the test interval. Based on pure inert gas during the first cycle, the compositional evolution of the circulating gas is monitored online with an infrared spectrometer.

The gas injected was pure Argon and the gases sampled by stainless steel sample cells were mainly argon, nitrogen and CO_2. Very rapidly, the presence of nitrogen was observed coming from the excavation phase, of CO_2 that reached a partial pressure of 10^{-3} bars, and of alkanes associated to organic matter naturally present in argillaceous rock. In addition, after a few weeks, it was observed that water seeped into the borehole at a rate of 0.5 to 0.8 litres per month. Since this water is produced in inert environmental conditions, it may have a composition very close to the interstitial water. This water produced by the boreholes will be analysed at a later stage.

Feedback from this experimental phase was used to adapt protocols for the preparation and installation of the equipment and to adjust the different phases for water and gas circulation in an additional installation at 490 m depth, also including two boreholes. On-line monitoring of the gas that had formed was carried out with an infrared spectrometer, complemented in the 490 m drifts with a Raman spectrometer. This on-line follow-up enabled to adjust the results of the different circulation cycles sample analyses.

4.3.6 KEY experiment: Sealing Device Tests at 490 m

In a specific drift (drift GKE) at the main level of the Bure URL, Andra tested a part of a drift sealing device. More specifically, it intended to demonstrate the possibility of controlling and limiting damage on the drift wall so that the overall seal permeability remain less than or equal to 10^{10} m/s.

The main objective of the KEY experiment was to test feasibility of limiting the axial permeability of the EDZ developed around a drift. The experiments used the technique of interrupting the axial hydraulic connectivity of the EDZ by creating a set of hydraulic cut-offs. These hydraulic cut-offs are narrow radial trenches filled with a low permeability swelling material (bentonite).

The EDZ conceptual model retained for the assessment of the Andra report “Dossier 2005” relies on observations made in the underground Mont Terri Laboratory, on the definition of the impact of excavation, and numerical simulations of the mechanical behaviour of argillaceous rock.

The disturbed zone was identified through geophysical survey (micro seismic borehole logs, ultrasound tomography and surface wave measurements). It is only about 1 to 1.5 m around the GMR drift, the least affected by the impact of neighbouring works.

At -490 m, the most argillaceous level, only the section of fractures closest to the wall has permeability higher than that of the undisturbed clay (between 10^{-8} and 10^{-11} m/s). In the GMR drift, the most representative of an insulated drift, the extension of the highest permeability zone is about 0.5 m at the wall horizontally and 1 m at the floor of the drift vertically (0.2 to 0.5 times the radius of the drift).

Given the available knowledge on EDZ, these fractures with higher permeability than the intact rock may form preferential transport paths. The solution studied to interrupt these paths at the drift and shaft seals is to create narrow slots (15 to 30 cm) filled with swelling clay and of sufficient length to intersect the damaged zones (for example, slots approximately 2.5 m long for a 6 m-diameter drift), without removing the lining. The use of multiple slots provides an impermeable barrier that interrupts the continuity of the damaged zone. The pressure from the clay as it swells in the slot tends to recompress the zone damaged by the excavation and prevents the slot from being bypassed. The feasibility of this concept and the installation of one plug of swelling clay separated by backfill have been tested in the

Canadian URL under the TSX experimentation programme. Although the host rock is granite, some of the technical aspects tested during this programme can be transposed to the Meuse/Haute Marne site.

The KEY Experimental Concept

Experiments carried out at the Mont Terri laboratory and the URL focused on thin radial slots with the aim to:

- Demonstrate the feasibility of creating these slots;
- Demonstrate the feasibility of filling up a slot with bentonite, in particular a vault;
- Assess the effectiveness of radial slots with respect to the problem of hydraulic short circuit; and
- Verify the effectiveness of applying swelling pressure.

The EZ-A experiment carried out in 2004 at the Mont Terri laboratory provided technological information (creating and filling slots) and scientific information on the behaviour of thin radial slots.

The objectives of the KEY experiment (Figure 18) optimized following the operation feedbacks of the EZ-A experiment are as follows:

- Characterization of the damaged and disturbed zones. It was carried out by implementing several methods: structural analysis of core samples, micro seismic logging, seismic refraction and surface-wave measurements, permeability to gas and water measurements with several removable or fixed devices equipped with chambers of various lengths;
- Assessment of the effectiveness of the radial slots concerning the problem of hydraulic short circuit consisted of comparing the results of tests on the interference of gas between vertical drillings carried out from the floor of the drift (an area of about 6 m^2). The tests were carried out before and after the excavation and the filling of two 7 cm thick slots with resin at 2m depth;
- Checking the effectiveness of applying confinement pressure in the slot consisted of measuring the progress and velocity of the compression waves in the near vicinity of a slot during pressure cycles exerted by flat jacks on the walls of the slot. The tool consisted of geotechnical instruments (inclinometers and extensometers) and a velocity survey device made of four probes with piezoelectric sensors (receiver-transmitter) including one inside the flat jacks. The 33 cm thick slot was carried out at 2 m depth from the drift floor. After removing the flat jacks, it was filled with bentonite and equipped with a hydration system to start saturation of this engineered barrier.

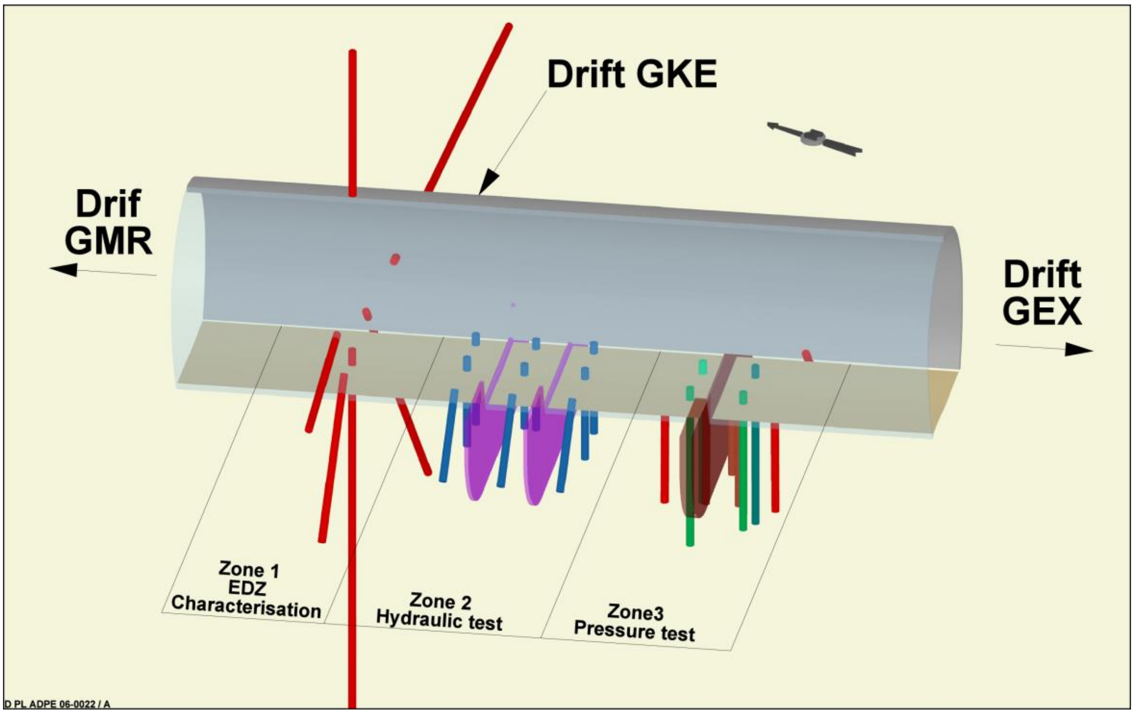

Figure 18 KEY experimental concept

Methodology implemented for the KEY experiment:

The EZ-A test has demonstrated the feasibility of radial slots and enabled us to develop the prototype of a saw to perform radial slots around a 2.5 m deep shoe horse shaped drift. This prototype was used to perform three slots in drift GKE:

- Two 7 cm thick slots at 2 m and 2.1 m depth; and
- One 33 cm thick slot at 2 m depth.

Creating out these slots did not raise any problem; the walls remained vertical and stable. It is to be noted that the 33 cm thick slot for testing the impact of inflating pressure remained open and stable for about a month (without support) before it was filled with bentonite. Thus, the KEY experiment confirms the feasibility of making radial slots in Callovo-Oxfordian clay.

Characterization of the disturbance of the damaged and disturbed zone around the drift:

Several measuring methods were used to assess the extension of these damaged and disturbed zones around the GKE drift according to different parameters:

- Structural analysis of the core samples to establish the presence of fractures and define the fracture density according to depth;
- Under the floor and at the bottom of the drift wall, the intrinsic permeability remains below 10^{-18} m^2 starting at one-meter depth. The boreholes at 2 m depth are therefore suitable to test the effectiveness of the slot with respect to hydraulic short circuit;
- Shearing fractures were identified around the drift, in particular in the slot under the floor. The measurements of P wave velocity carried out under the floor, show that the velocity does not evolve steadily in the first two meters. This may indicate that high velocity zones (with a velocity close to that of the intact rock) alternate with lower velocity zones corresponding to those fractured by the chevrons.

Testing the effectiveness of slots with respect to hydraulic short circuit:

The intrinsic permeability measured initially during air permeability tests range between 1×10^{-9} m^2 and 5×10^{-14} m^2 in the first meters under the floor, except for three out of nine chambers showing permeability equivalent to that of the saturated undisturbed rock (below 1×10^{-20} m^2). This demonstrates the heterogeneity of the permeability under the drift floor in the 3 m × 3.2 m test zone.

Permeability measured between 1 m and 2 m during air permeability tests carried out before slot construction is close to those measured in the intact saturated rock.

After excavation and filling of the slots, the helium tracer tests showed the interruption of hydraulic connections and the role of the sealed barrier of the thin radial slots filled with resin.

4.4 Activities in the URL 2006-2009: the 2009 report and Cigéo Design and Safety Options

4.4.1 Revision of the Project Development Plan

According to the 2006 Planning Act, the overall PDP was revised to organize the studies and investigations to be conducted simultaneously between 2007 and 2014. The purpose of the PDP is to provide the required knowledge sufficient to constitute corresponding deliverables at the different deadlines prescribed by the Planning Act, the PNGMDR (French’s Waste Management Plan), and the Development Plan.

Similarly, a rationale based on a flexible structure of those programmes helps to integrate the needs for intermediate data, as identified by reviewers on a specific subject.

The R&D programme was organised around nine main sub-programmes, two of them structuring the work to be carried out in the URL. This period of activity led to the 2009 scientific report providing the basis for DGR safety options and DGR conceptual design.

Experimentation and demonstration test programme at the Laboratory

As a key element of the study programme of the geological medium, the Laboratory accommodates new experiments and test campaigns. It will focus on building techniques for underground installations and, more generally, on the reversibility and safety of the disposal process. Those research projects were compared with the work carried out in foreign underground laboratories, especially at Mont Terri, Switzerland, and Äspö, Sweden.

Surface survey programme

Survey work (boreholes, 2-D and 3-D seismic) complete and homogenise the acquired data concerning the transposition zone. After 2009, they provided a detailed geometric model of the Callovo-Oxfordian formation in preparation for the implementation of the repository (with a level of detail at the metric order corresponding to the scale of the underground structures under study).

Scientific programme

The scientific programme mobilises a large spectrum of investigations and incorporates Andra's new responsibilities concerning the long-term behaviour of waste packages. It is based on the results acquired since 1994 and benefits, together with the Laboratory, from the results of the experiments performed in the Callovo-Oxfordian stratum. Its purpose is to refine the description of processes, to complete existing databases, especially because of full-scale tests, to develop tools, and to associate within a single approach the advances regarding engineering and the phenomenology of the repository.

Simulation programme

Simulations help to acquire information on the medium and long terms that only experiments may provide. They help to describe the phenomenological evolution of the repository and of its surrounding geological environment as early as the phase of reversible operation and over the very long term. They also help in the repository design and constitute a useful tool to assess reversibility and safety conditions, during operation and over the long term. Besides the results of the other programmes (experimentation, surface survey, scientific), the programme relies on modern digital-calculation tools and contributes to their development.

Surface engineering study and technological test programme

The programme includes studies aiming at developing the design principles of the repository and then at establishing the specifications of its installations and equipment. The planned operating techniques will be optimised and checked during tests and by technological demonstrators.

Information and consultation programme

The programme describes the actions and tools to be used by Andra in its communication and information efforts. The purpose is to provide everybody with the necessary elements to understand the project. Based on those elements, this programme describes the framework and the subjects on which Andra will propose a dialogue to stakeholders. Those exchanges preceded the public debate held in 2013 and served in its preparation.

Environmental and repository observation and monitoring programme

The purpose of the programme is to design and to make available suitable measuring means in order to observe and monitor the repository and its surface environment. It proposes the implementation of both a perennial environmental observatory and the establishment of an initial reference state (surface and underground) in the near future. In the latter case, the purpose would be to study the impact of the disposal facility on its environment during operation and after its final closure.

Package management, monitoring and transport programme

The programme must first help to establish a detailed inventory of all waste concerned by the project. HL and IL-LLW will not be accepted automatically in the facility. The programme must therefore describe relevant specifications and package-acceptance criteria, particularly with regard to Andra's control operations. Last, it must also identify and provide appropriate means and fittings for transporting the waste from production or storage sites towards the disposal facility.

Storage programme

Research on the durability of storage means is pursued with a view to designing new storage capabilities meeting the needs identified by the French National Inventory of Radioactive Materials and Waste. The study on storage/disposal complementarity involves the upstream definition of possible storage scenarios and options, such as storage on production sites and/or buffer storage or thermal decay storage on the disposal facility site.

4.4.2 URL R&D Programme 2006-2009

In application of the new PDP, the URL entered into a new construction phase with updated objectives:

- Intensification of the research on THMC coupled process; and
- Technological experiments and tests.

In parallel to the elaboration of the URL R&D programme starting in 2008, Andra decided to hire a new construction contractor and to take over the operation of the URL. Resuming the construction 2008 was a transitional period in the R&D plan. Limited new experimental drifts were constructed but accesses to future experimental zone were prepared (Figure 19).

One of the main difficulties that Andra had to resolve before launching the new R&D plan was to define clear and robust procedures and re-organize the functioning of the URL to be able to combine safely construction, operation and R&D concurrent activities.

During this period, the main activities were oriented towards:

a) Improving excavation technics and EDZ occurrence and evolution. During this period many technics were tested, such as the excavation of a circular drift with a road header in the direction of the minor and major horizontal in-situ stresses. After using only sliding arches during the first phase, softs supports were tested such as high thickness shotcrete or compressible beams. All these experiments led to an understanding of the fracture developments around drifts and their evolution. (See OHZ ORS experiments.)

b) Testing the first micro tunnelling machines for excavation of HLW disposal cells as well as their behaviour with or without liner (See ALC Experiment).

c) Fundamental understanding of rock properties *i.e.* gas migration in clay rocks, understand the thermo-hydro-mechanical properties of the rock (See TED Experiment), interactions between materials (Cement/Iron/Glass) and rock.

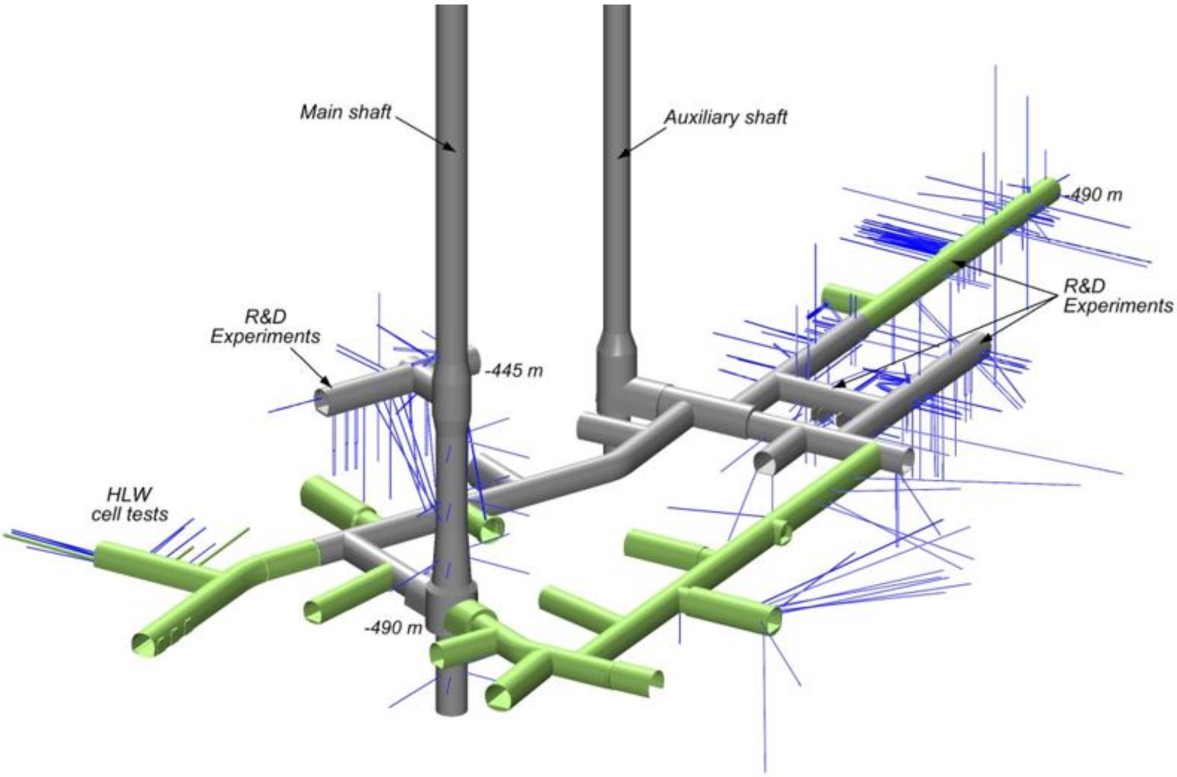

Figure 19 *Scheme of URL construction and experimental zones with new experimental zones in operation during 2006-2009 (Green zones)*

Finally, considering the seal of Cigéo, natural hydration of sealing plug at small scale started during this phase.

4.4.3 OHZ and ORS Experiment: Understanding Hydro Mechanical Behaviour of Claystone

The characterization of the hydro-mechanical behaviour of claystone started with measurements performed from the ground surface (boreholes, geophysical campaigns). These measuring methods allowed to obtain geo-mechanical data which were however fragmented and derived from small volumes of soil (boreholes) or were indirect (in case of geophysical campaigns). Moreover, claystone cores extracted at 500 m depth undergo de-confinement that may modify some of their properties.

The knowledge of the fracturing that occurs during the early stage of the drift excavation in claystone is one of the major questions to be answered in order to estimate the geometry and extension of the damaged zone. Geological mapping of the drift front face from the beginning of the excavation and systematic analysis of borehole cores provide a significant amount of data on the orientation of the fracturing planes induced by excavation process.

It was thus possible to build a 3-D model of the geometry of the fracture network (Figure 20). The damage to the rock is characterized by the initiation of shear fractures from the excavation front face and extensional/unloading fractures after the excavation front has passed. If the nature of induced fracturing does not depend significantly on the direction of the excavation, its expression and particularly the extension of the zone where the different kind of fractures coexist depend on the orientation of the drift with respect to the major horizontal stress.

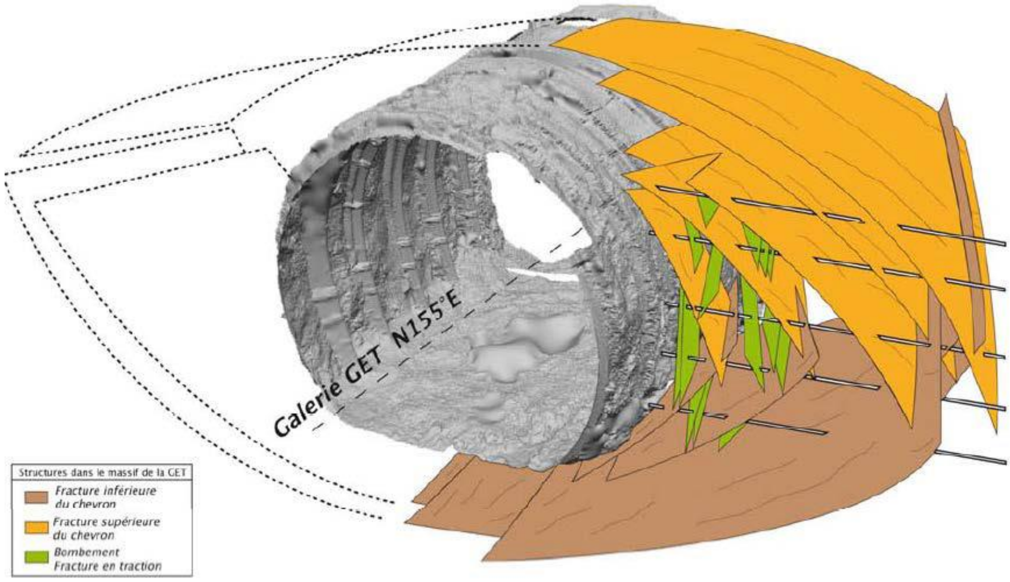

Figure 20 *Fractures induced during excavation process*

The induced fracture network has an ellipsoidal shape that can be described in the direction away from the drift wall in the following way:

- A connected fractured zone where several kinds of fractures coexist - shear and extensional fractures more or less well connected to each other; a presence of mixed fractures is also observed. These fractures have a wide range of geometric apertures, up to several millimetres;
- A "discrete" fractured zone beyond the connected fractured zone, where only the ends of some of the shear fractures appear; these are not physically connected to each other, with infra-millimetre apertures. A maximal extension of this "discrete" fractured zone can reach up to one gallery diameter (from the drift wall).

Systematic characterization of rock behaviour (OHZ experiment) around drifts (deformation, interstitial pressure) and rock/ support interaction (ORS experiment) is carried out in the underground laboratory during the excavation of every new drift and is monitored over time. This experimental strategy allows the comparison of the behaviour of drifts built with different excavation/support methods.

Convergence measurements sections, and "reinforced measurements sections" consisting of a least four radial extensometers, are installed in most of the drifts to monitor rock deformation. These are completed by multipacker systems to monitor the interstitial pressure field and to perform hydraulic tests to determine the permeability. When possible, measuring equipment in the rock mass is installed before excavation ("Mine-by test") in order to monitor the deformation and the interstitial pressure evolution during all the construction activity period.

4.4.4 ALC Experiment: Micro Tunnel Excavation Tests

Experiment aims

The design of HLW disposal cells studied for high level waste consists of 40 m long, 70 cm in diameter horizontal micro-tunnels. To prevent against rock deformation, the micro-tunnel is lined with a casing allowing the retrieval of waste canisters. Cells are finally sealed with a swelling clay plug, itself confined with a concrete plug (see Figure 9 in page 18).

One of the objectives of the technical and scientific programme carried out in the URL is to verify the feasibility of the excavation of such micro-tunnels in the 500 m deep argillaceous rock formation, and to study the thermo-hydro-mechanical behaviour of such disposal cells and the surrounding rock mass. With this aim, specific experiments have been developed to study:

- Hydro mechanical response of the argillaceous rock to the excavation;

- Mechanical behaviour of the micro-tunnel after excavation;
- Behaviour of the steel casing under rock deformation and thermal stress; and
- Hydro mechanical response of the argillaceous rock to a thermal stress.

Micro tunnel: excavation tests

Excavation tests of micro-tunnels are performed using a guided auger drilling machine (Figure 21).

Figure 21 *Views of the micro tunnelling boring machine*

Prior to the excavation, pore pressure measurement devices are installed in standard diameter boreholes at different distances from the theoretical trajectory of the micro-tunnels in order to monitor the hydro-mechanical impact of the excavation on the rock mass behaviour (Figure 22a) . Both pore pressure and temperature are measured in 20 cm long test intervals (3 to 5 test intervals per borehole) saturated with water and isolated from the rest of the borehole with sealed packers. The devices are installed several weeks before the excavation of the micro-tunnels to give enough time to the pressure in the test interval to reach the rock mass pore pressure.

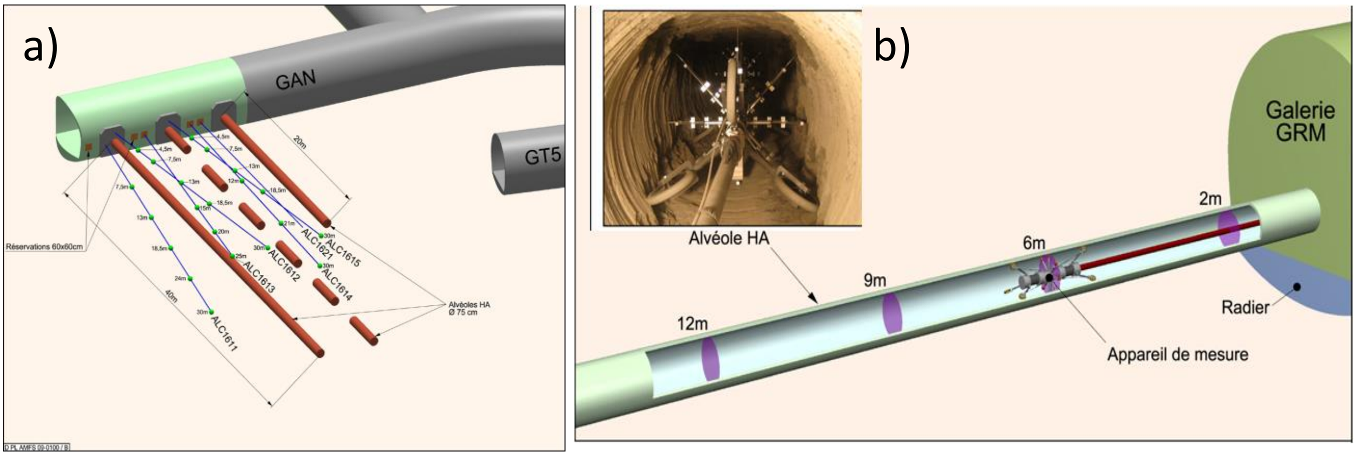

Figure 22 *Interstitial pressure measurements boreholes (a), micro-tunnel convergence measurements (b)*

After excavation, a 3D scan and video inspection have been carried out in one of the tunnels, with equipment specially designed for this purpose, to obtain a qualitative characterization of the micro-tunnel: trajectory, geometry and quality of the excavation, casing alignment.

Convergence measurements were then carried out in the micro-tunnel to investigate its mean-term deformation behaviour (Figure 22b). The device used for this purpose consists of several instrumented sections mounted on wheels, pushed inside the micro-tunnel to the target measurement location. Each section allows the measurement of displacement along four diameters by means of potentiometers. Once installed at the desired location, the sensors are put in contact with the micro-tunnel wall using pneumatic jacks. Each section is also equipped with a temperature and relative humidity sensor to monitor the potential impact of atmospheric conditions in the micro-tunnel on the deformation behaviour.

All sensors are connected to a centralized acquisition and management data system (SAGD).

Main results

The first phase of the micro-tunnel excavation test programme was carried out in 2009. Three micro-tunnels 10 to 20 m long were excavated in two directions relatively to the stress state orientation. Excavation of a 20 m long micro-tunnel took about 3 days.

Interstitial pressure recorded during and immediately after the excavation of the micro-tunnels show important overpressures generated by the excavation.

Overpressure reaches 35 bars at a distance of 0.9 m from the micro-tunnel wall 18 hours after excavation, and propagates in the host rock. The overpressure peak at a distance of 1.8 m from the micro-tunnel wall is reached 21 days after excavation, with a value of 20 bars. These overpressures are in some cases significantly higher than the one predicted by modelling. This suggests the influence of parameters that were not taken into account in the modelling, as pressure of the drilling machine on the excavation front, or temperature increase induced by the drilling (the micro-tunnel is not ventilated during excavation).

4.4.5 TED experiment: Rock Mass Hydro-Mechanical Response to Thermal Solicitation

The “Thermal Experiment Deux” (TED) experiment principle was to measure the evolution of temperature, pore pressure and deformation around three heaters located parallel to each other in the Callovo-Oxfordian clay.

The TED experiment continued the research conducted in the TER experiment, first thermal experiment starting in 2005, with some enhancements. In particular, attention has been paid towards the uncertainties regarding the sensors’ location and the limitation of temperature and stress field influence of the nearby drifts. The main difference between the TER and the TED experiment is the number of heaters: one heater in the first test and three in the second one.

The boreholes are drilled parallel to the maximum horizontal stress and are placed about 2.7 m away from each other in a consistent ratio with the repository concept. This configuration includes planes of symmetry with no-flux boundary conditions between two heaters. This geometry allowed monitoring the thermal overpressures and their evolution in this no-flux plan.

Layout of the experiment and instrumentation

The TED experiment is located in the GED drift at the main level of the URL. The overall layout of the experiment can be seen in Figure 22. It includes 3 heating boreholes (TED1201 to TED1203) and 23 instrumented observation boreholes:

- 12 boreholes for the measurement of water pressure (10 monopacker boreholes TED1250 to TED1259, 2 multipacker boreholes TED1240, and TED1241). In each piezometric chamber, the temperature is measured. These boreholes are backfilled with resin to ensure very low permeability and a low compressibility;
- 9 boreholes for the measurement of temperature (TED1210, TED1212 to TED1219) representing 90 temperature sensors. The boreholes are backfilled with a cement-bentonite grout formulated in a way that it reproduces the low permeability of the Callovo-Oxfordian. The temperature sensors in the rock mass record the temperature within the heated zone as well as in the non-heated zone;
- 2 boreholes for the displacement measurement (2 extensometers and inclinometers in 2 boreholes TED1230 and TED1231).

The three horizontal heaters are 4 m long and have been installed at the end of 160 mm diameter and 16 m long boreholes in order to avoid the influence of the seasonal temperature variations of the GED drift and, more generally, to avoid the THM influence of this drift. The three boreholes are cased all along (Figure 23).

The void between the casing and the claystone has been grouted with a classical grouting, just as the deformation measurement boreholes (TED1230 and TED1231). 69 temperature sensors have been installed in the 3 heater boreholes (TED1201 to TED 1203) with 51 dedicated to temperature measurement on the external casing of the boreholes. Eighteen are placed in the heater in order to control and adjust its temperature.

In order to optimize inverse problem analysis, special attention has been paid to the reduction of uncertainties regarding the sensors location in the boreholes. Possible sensors location errors were indeed found to be a problematic issue for analysis and parameter determination in TER experiment. All the coordinates of the sensors have been measured.

Since the Callovo-Oxfordian claystone exhibits stiffness and strength anisotropy (cross anisotropic behaviour as many sedimentary rocks), the boreholes have been positioned both vertically and horizontally to the heaters to measure parameters in both orientations with respect to the bedding.

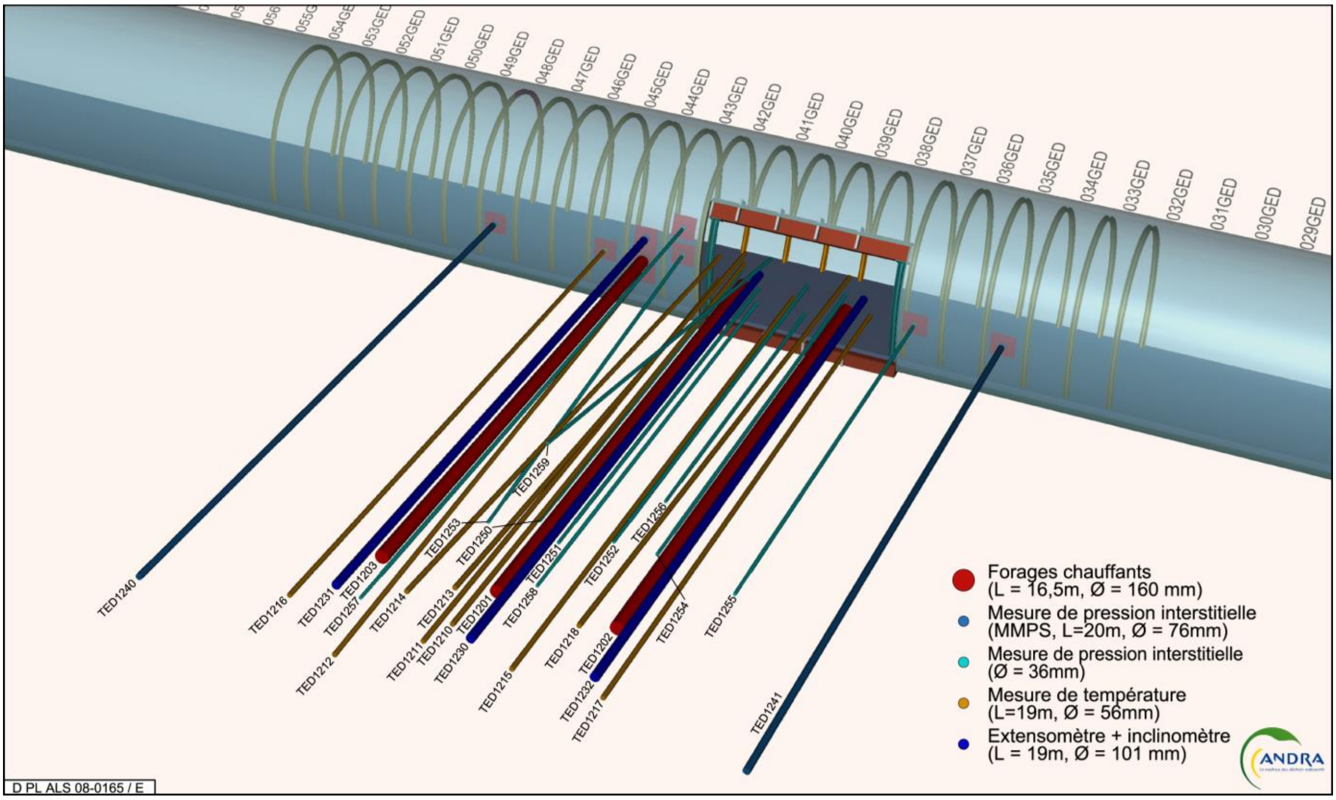

Figure 23 Design of the TED experiment

The power sequences applied in each heater has been designed to be maintained long enough to achieve a thermal quasi-steady state. This design was meant to separate the steady state and transient regimes and then to facilitate the distinction between the time-related parameters (heat capacity) and the permanent ones (thermal conductivity). Moreover, the several steps at distinct power (25 %, 50 % and 100 %) intended to study the effect of several ranges of temperature increase on the rock mass behaviour.

The nominal power to be applied in each heater was designed to achieve a maximum temperature of 90°C on the rock-heater interface when the three heaters were switched on. The highest temperature of 90°C corresponds to a requirement considered in the French repository concept. The history of the applied power in TED experiment can be divided into three main stages, namely two heating stages and one cooling stage (Figure 24).

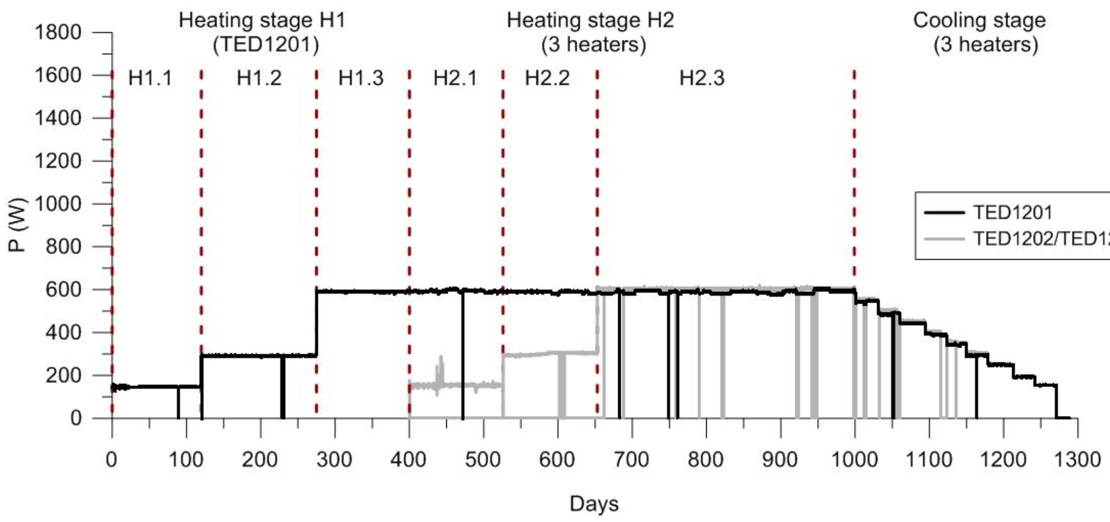

Figure 24 *Power history applied to the three heaters during the different stages*

The first heating stage started on 25 January 2010 (day 0) when only the central heater TED1201 was turned on. This first stage included three steps (starting respectively at days 0, 120 and 275) of approximately 4 months:

- H1.1: a power of 150 W (25% of nominal power);
- H1.2: a power of 300 W (50% of nominal power); and
- H1.3: the nominal power of 600 W.

At day 400, the second heating stage started with the three heaters turned on in order to investigate effects of the additional thermal loads. It lasted 20 months. While the central borehole TED1201 was maintained at the nominal power during the whole stage, the same heating load was applied to the two additional boreholes TED1202 and TED1203, following the steps of TED1201 in the first stage:

- H2.1 (starting at day 400): a power of 150 W applied to TED1202 and TED1203;
- H2.2 (starting at day 526): a power of 300 W applied to TED1202 and TED1203; and
- H2.3 (starting at day 653): the nominal power of 600 W applied to TED1202 and TED1203, the three heaters having been maintained to their nominal power during one additional year.

On day 999, the cooling stage started. After the power was shut down the experiment is not considered to be finished. The decrease of temperature up to the initial ones associated with a pressure recovery was follow to better understand the THM behaviour of the Callovo-Oxfordian.

Main outcomes of the experiment

Thanks to an elaborate heating and cooling history and an extensive instrumentation, the TED experiment has provided important information about the Callovo-Oxfordian THM behaviour and its response to thermal loading.

In particular, it has highlighted the pore pressure response to a temperature increase. First the pressure increases, too, due to the discrepancy between the thermal expansion coefficient of the pore water and of the solid skeleton. Then, the generated overpressures dissipate, the dissipation rate being governed by the hydraulic conductivity of the medium. The TED experiment has also shown the anisotropy of the Callovo-Oxfordian THM behaviour, affecting both its thermal and hydraulic response to a thermal load.

Regarding the evolution of the Callovo-Oxfordian properties, it comes out that the thermal properties are constant during the loading but that the change of water thermal expansion coefficient and water viscosity with temperature should be taken into account to reproduce the in situ measurements. As for the permeability field, it is not affected by the heating.

An important work of THM modelling aiming at validating and improving the THM models and represented predictive and interpretative calculations has been carried out. Some models were purely thermal while others included THM interactions. On a thermal point of view, it appears that the in-situ temperature field is perfectly reproduced by modelling and that the values obtained by back analysis are very close to those obtained in laboratory. The reproduction by the THM models of the measured pressure field is also quite good

Finally, the measured results and numerical interpretations have led to a better characterization of the THM properties and THM behaviour of Callovo-Oxfordian on the small scale.

4.5 Activities in the URL 2010-2015: detailed design of CIGÉO for Safety Option report in preparation of licensing application

The 2010-2015 periods were extremely active for the URL and many large experiments were launched. The objective was to provide scientific support to the Safety Option report submitted in 2016 for review to the French National Safety Authority (ASN). The work in the URL was also driven by designer needs in charge of the Detailed Technical Project to be submitted with the licensing file.

The Figure 25 shows the extension of the URL, at the end of 2015.

From the technical point of view the main experiments were related to the construction of an 80 m long drift built with a tunnel boring machine with segment fitter (GED). Soft supported drift and rigid supported drift were drilled with different kinds of support means and lining.

In order to prefigure IL-LLW component a drift, 9 m in diameter was built to accommodate the tunnel boring machine construction room.

A large experiment dealing with seal component started after 5 years of design many preparatory tests (see NSC experiment). This experiment complemented the 360° slot test (EDZ cut off) that followed up the KEY experiment.

In addition, many HLW cells were drilled with and without lining, one being more than 100 m long. Some of them served for a specific heating test.

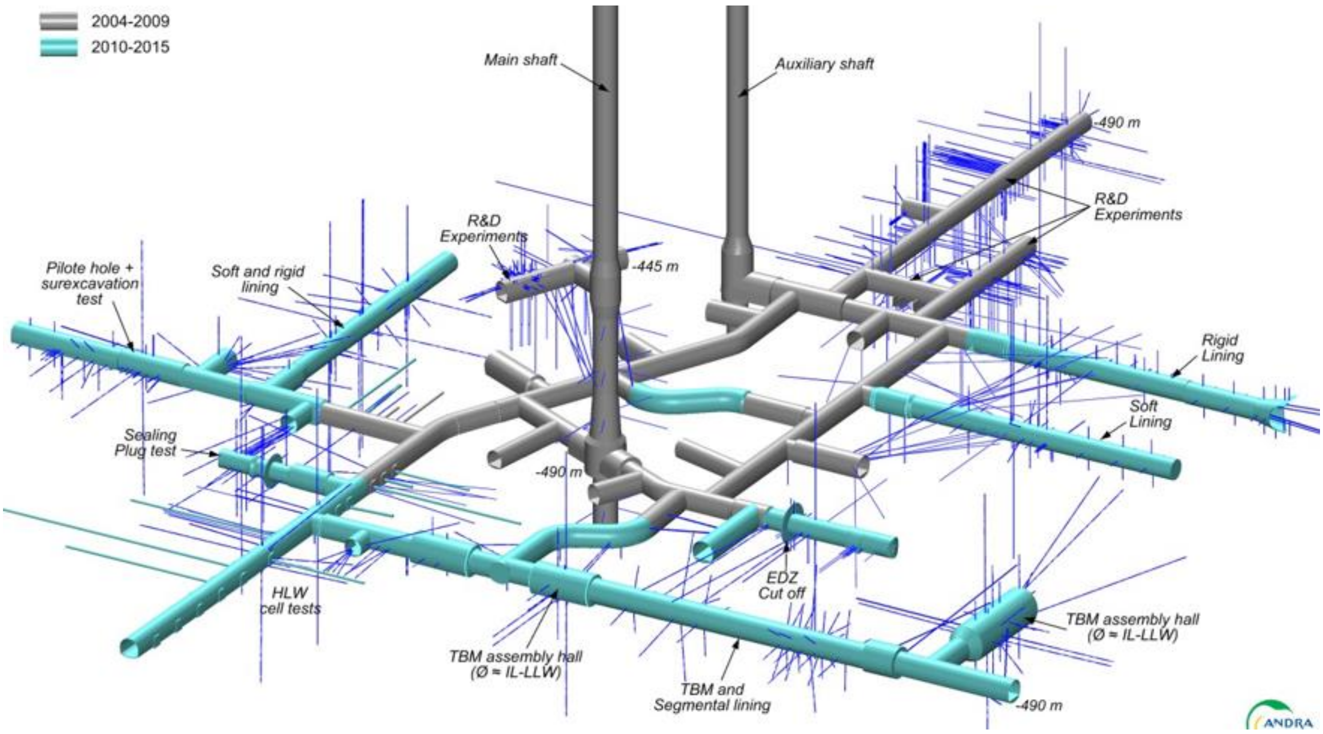

Figure 25 Scheme of URL construction and experimental zones with new experimental drifts in operation during 2010-2015 (Blue zones)

Considering the scientific programme, it could be noted that during this period a lot of results were obtained on material interactions with the host rock

This will be illustrated below by a corrosion experiment called MCO.

4.5.1 ALC: Full Scale Emplacement Experiment

Aim of the experiment

Following the TED experiment, another in-situ heating test has been planned and is still under operation and monitoring in the Meuse/Haute-Marne URL: the ALC full scale emplacement experiment.

The main aims of ALC full scale emplacement experiment performed were to demonstrate the construction feasibility of a High Level Waste (HLW) cell representative of the 2009 concept and to determine the impact of a thermal loading on the overall behaviour of the cell. The experiment has also been used to acquire new data on the THM behaviour of the surrounding rock and to compare them with those acquired in previous small scale heating experiments.

A general view of the experiment is shown in Figure 26.

The characteristics of the ALC1604 cell are as follows:

- Total length 25 m, including a cell head 6 m in length and a "useful" part 19 m in length, with a 1 metre-wide overlap zone between the sleeve and the insert;
- The excavated cell head 791 mm in diameter, with the installation of an insert 767 mm in external diameter (i.e. an annular space 12 mm wide at the radius) and 21 mm in thickness;
- The excavated useful part 750 mm in diameter, with the installation of a sleeve 700 mm in external diameter (i.e. an annular space 12 mm wide at the radius) and 20 mm in thickness;
- A base plate, a sleeve head plate and an insert head plate; and
- Thermal loading is applied over a length of 15 m at between 10 m and 25 m in depth.

All these characteristics (except for the length), meet the requirements for proving the 2009 concept.

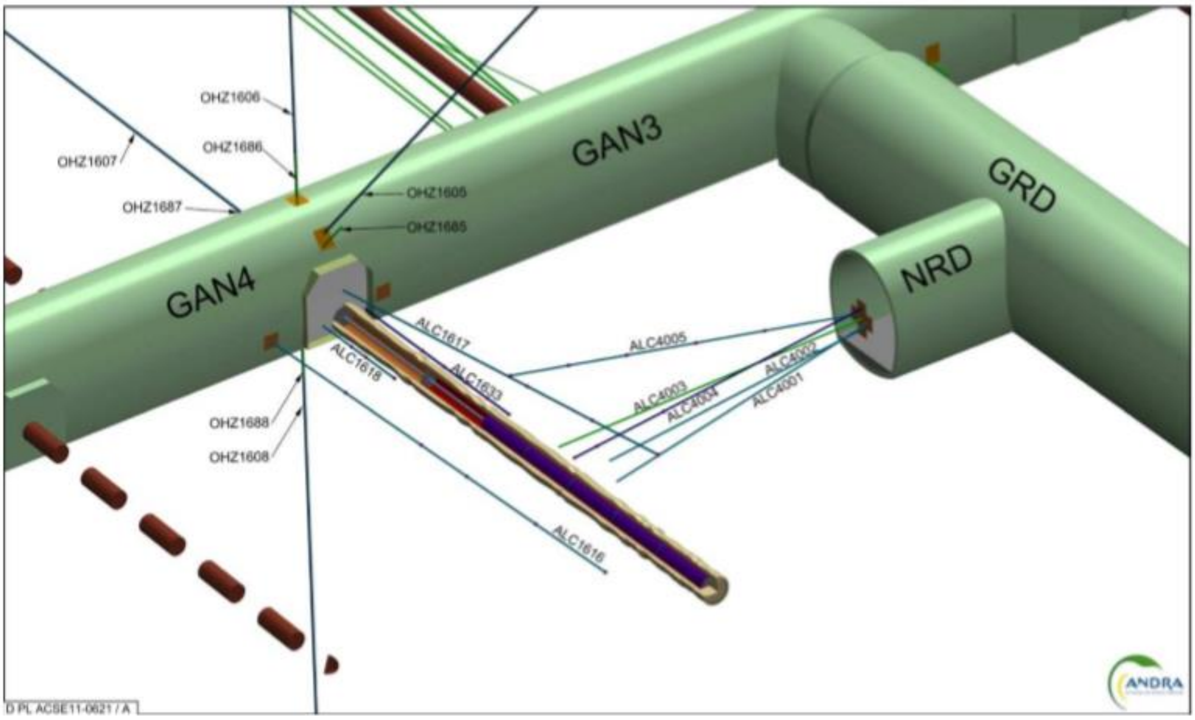

Figure 26 General view of the of the ALC full scale emplacement experiment

Figure 27 shows the location of the sleeve sections and insert sections equipped with sensors in the cell.

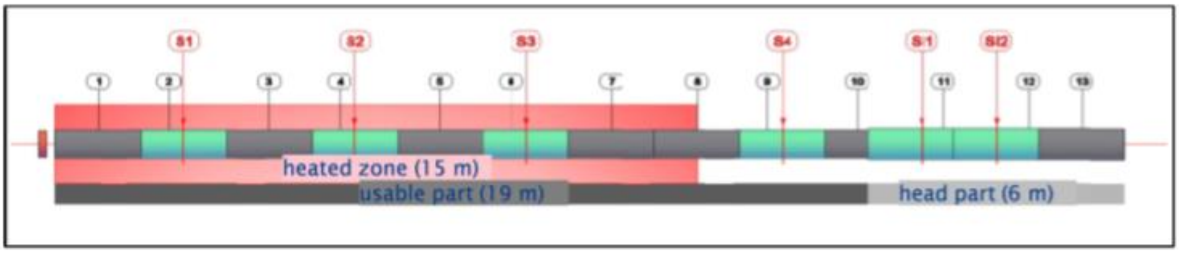

Figure 27 *Location of the section and insert sections equipped with sensors*

More than 200 sensors have been installed on the casing and in surrounding boreholes. After 2.5 years of measurements, the loss of sensors is less than 10%, which is mainly due to the thermal loading.

The heating system has an acceptable reliability with only 4 failures in 2 years caused by the control cabinet fans failing. These power cut offs had no impact on the overall THM behaviour of the cell.

Heating phase characteristics

Heating is provided by means of five heater elements, each of which is three metres in length and 508 mm in diameter. The power is monitored.

Each element is fitted with 6 transfer skids constructed in highly resistant plastic embedded in metal parts that are themselves welded to the heat source (Figure 28). These skids, which are equipped with small wheels, enabled the heater elements to be easily put into place by rolling them along pre-installed rails. The position of the heater elements is very slightly off-centred downwards by 2 mm.

Figure 28 *View of a heater element when it is installed left) - View of a heater/sleeve distance variation sensor section (right)*

After performing a short low-powered heating test (33 W/m) between 30 January and 15 February 2013, the main heating phase began on 18 April 2013 with a constant 220 W/m power supply for the 15 m occupied by the heater elements, at a depth of between 10 and 25 m in the cell. This power was calculated so that a temperature of 90°C would be reached at the sleeve wall after two years.

Main results

The hydro mechanical impact of excavation on the surrounding rock is consistent with the observations made during previous drilling campaigns. It results in pore pressure increase in the horizontal plane up to 2 MPa at 2 m distance from the cell wall and by a depression in the vertical plane. This difference in behaviour between the two directions is directly related to the anisotropy of mechanical properties of the Callovo-Oxfordian claystone.

Despite an initial annular space of 25 mm, the sleeve is subjected to a mechanical loading no later than 2 months after the drilling. This phenomenon can be explained by the partial filling of the annular space by rubble. The mechanical loading applied by the rock is localized in the horizontal direction (corresponding to the maximum extension of the fracture network around the cell) resulting in a radial bending of the sleeve. A similar loading process has already been observed on the sleeve of full scale cells as well as on reduced scale casing having the same orientation.

The THM impact of the thermal loading on the surrounding rock mass is consistent with the results obtained in previous reduced scale heating experiments. The heating leads to overpressure related to the difference in thermal expansion coefficient between pore water and rock, both in the horizontal plane and in the vertical plane of the cell. The thermal pressurization coefficient is between 3 and 5 bar/°C. Differences in time needed to reach the pore pressure peak are observed between the 2 directions due to THM anisotropy of the rock. The first numerical simulations of the experiment exhibit a good qualitative reproduction of the THM behaviour of the near field rock.

In agreement with results obtained in previous reduced scale heating experiments, the temperature increase leads to an acceleration of the mechanical loading applied on the sleeve (increase of the convergence rate). Once the annular gap is completely consumed in the vertical direction, the ovalization of the sleeve is blocked before decreasing gradually, indicating a decrease in load anisotropy. The experiment also allowed to validate the correct operation of the sliding connection between insert and sleeve to absorb its thermal expansion. Measurements show that thermal expansion of the sleeve occurs both towards the end and towards the head of the cell.

4.5.2 NSC Experiment: Sealing Plug Experiment (Noyau de SCellement)

During the excavation of a shaft or drift, the rock properties around the underground openings could be altered due to the level of the ratio of in-situ stresses over strength of the rock. And even in some cases, the rock mass could be fractured. One concern regarding waste disposal is that the associated disturbance and damage created in this area around these excavations might change the favourable properties of such formations and thus negatively impact the repository performance. To limit radionuclide migration along drifts and through the EDZ, seals will be installed in drifts and shafts. These seals will be composed of swelling clay (mainly bentonite) core in between two concrete plugs. After natural hydration from the surrounding rock mass, the bentonite will swell and apply radial pressure against the drift wall.

In this context, Andra designed a large scale sealing experiment which is called NSC (French acronym for Noyau de SCellement). The main objective is to back analyse the equivalent permeability of the seal in place in order to check the efficiency of such seal. Before reaching this ambitious goal, numerous outputs will be provided by this experiment on the effect of the hydration of the seal: evolution of the permeability (at the interface seal/claystone and in the surrounding rock mainly the damaged zone), the pressure build up on the concrete plug. The experiment is not a demonstration of the seal emplacement technique. Many sensors have to be installed in the seal and around it and results have to be obtained over a reasonable timescale, thus the water injection in the plug was forced. That implies that properties and emplacement of the seal could not be fully representative of the forecast seal.

For example, for the sealing material, 3 criteria were set at the beginning: i) hydraulic conductivity at saturation equals to 10^{-11} m/s, ii) swelling pressure between 1 and 3 MPa, and (iii) reasonable time for hydration to reach fully saturation in several years. A first major step was the definition of this material and this was carried out by the French Atomic Agency (CEA/LECBA). The finally chosen material is a mixture of Sand/Bentonite (MX80) in proportion 60 % and 40 % respectively in the form of brick (300 x 200 x 100 mm). With this S/B mixture, the permeability criterion is respected. For the other criteria, swelling pressure depends on the void ratio during the construction of the seal and the time for hydration depends on the number of the hydration membrane inside the S/B mixture.

It was chosen to put NSC experiment at the end of a drift of 4.6 m diameter (in GES drift see Figure 23) in order to be sure that flow goes preferential along the seal. The experiment is composed of 4 zones (Figure 29): injection chamber (zone 1), seal (zone 2), concrete plug (zone 3) and water thigh drift (zone 4). This seal is implemented in a drift of 5 m long and 4.6 m of diameter (inside the GES drift (see Figure 29).

The injection chamber will be the upstream part during the performance test and the concrete plug will be the downstream part. To avoid leakage between the two faces of the seal, all instruments installed within the S/B sealing (sensors, hydration membranes and surrounding boreholes) must to be wired towards the injection chamber passing through the concrete plug in 2 tubes system that guarantees the test tightness. All the wires pass through 6 “instrumentation” boreholes between injection chamber and NRM niche. The detailed design of the instrumentation, delivery and installation are done by the joint venture Aitemin and Solexperts, except for the acoustic measurements into the concrete plug which are done by INERIS.

The monitoring instruments, which have been installed in the experiment, are divided in different cross sections. In the seal and at the interface with the concrete plugs (upstream and downstream) are 319 sensors (humidity sensors: 64 capacitive, 64 psychrometer and 16 FDR; pore pressure sensors: 99; total pressure sensors: 76) and 6 hydration membranes. Between each hydration membrane, the thickness of the S/B seal is 1 m. The maximal distance inside the S/B mixture from hydration membrane is therefore equal to 50 cm. For this distance, the time for hydration is estimated at 3 years. Thus the second criterion is respected.

The hydration membrane at the interface between the concrete plug and the seal is divided into 12 independent areas (Figure 29). This specific design allows to distinguish water fluxes from the near-field of the damaged zone, the interface between claystone and seal and water coming through the seal during the performance test.

The concrete plug (zone 3) (Figure 30) will be monitored with deformation, displacement, temperature and acoustic sensors. Both concrete plugs of the zone 1 and 3 are dimensioned to a swelling pressure of 7 MPa. The chosen concrete is a low-heat concrete with no reinforcement.

The access gallery in GES (zone 4) is made watertight and a cut-off of 2 m depth will serve to inject water into the damaged zone around the drift). Indeed, scoping calculations were performed using Bright code and showed that the ventilation into the access drift will remove the water of the damaged zone across the seal. This desaturation will be harmful to get a full hydration of the S/B mixture. To counteract this effect, water will be injected into the cut-off.

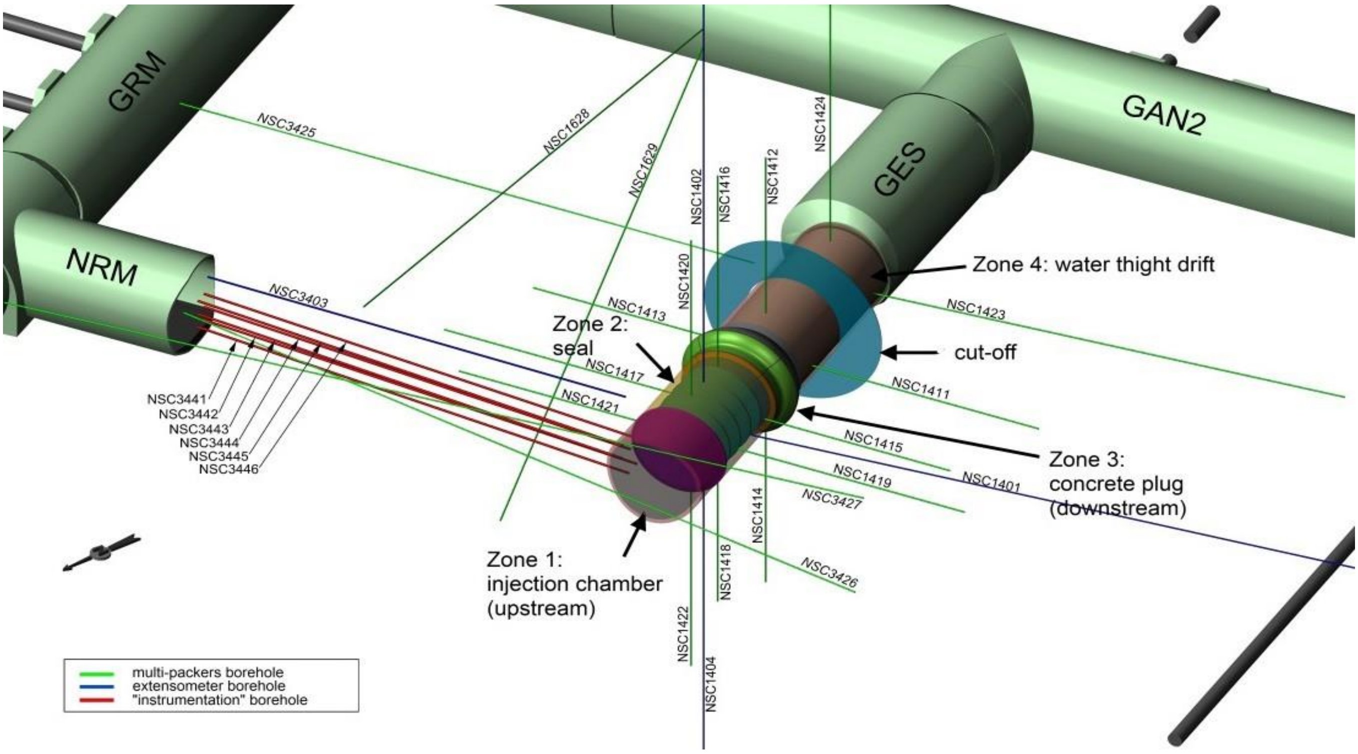

Figure 29 *General layout of the NSC experiment in the Andra's URL*

Surrounding the GES drift a total of 23 boreholes will be equipped with multi-packers systems to monitor pore pressure (19 boreholes) and the other boreholes will be equipped (4) with extensometer. In the multi-packer boreholes, hydraulic tests will be repeated to monitor the evolution of the hydraulic conductivity around the seal in respect to the swelling of the S/B mixture.

The GES drift was excavated in 2012 and all the instrumentation inside GES drift and S/B mixture was installed in 2013. During the construction of the S/B seal, volume and mass of the S/B mixture was controlled. Those measurements were used to estimate the dry density of clay material in the seal and therefore estimate the swelling pressure. The estimated dry density of clay material and swelling pressure are close to 1.45 kg/ m^3 and 2.5 to 3.4 MPa respectively. The third criterion could be met.

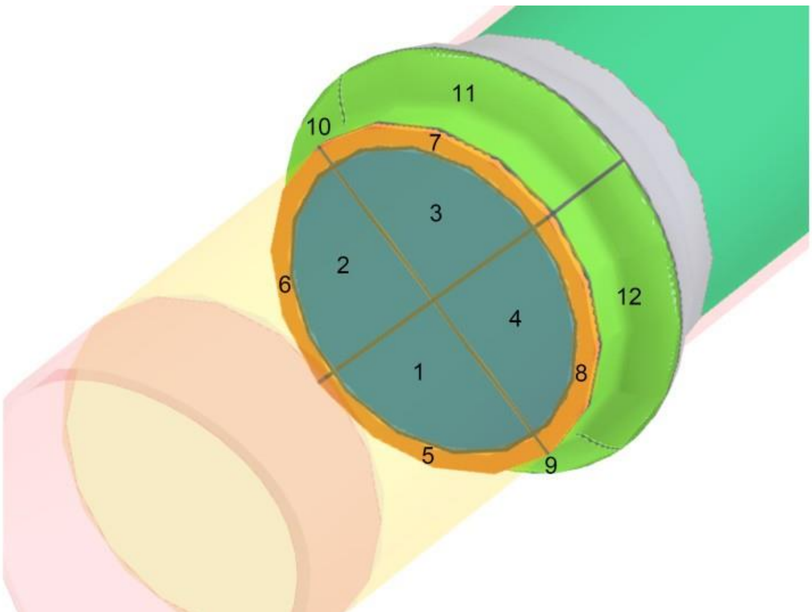

Figure 30 *NSC: Detailed layout of the membrane at the interface with the concrete plug (zone 3)*

4.5.3 MCO Experiment: Corrosion at the Carbon Steel – Clay Pore Water or Gas Interfaces

Aim of the experiment

In order to understand the corrosion processes of carbon steel materials in contact with pore water and/or gas in clay environment under reduced conditions at 85°C, an in-situ experiment called "MCO" was carried out.

In a test chamber drilled in clay rock, samples of low-alloy carbon steel reacted either in "clay pore water" (actually a liquid phase initially made of synthetic clay gradually replaced by water seepage) or in an atmosphere of gases released by the host rock and by corrosion processes. Samples series were removed from the test chamber at given times (between 3 and 30 months), and the metal loss and corrosion rate (CR) were quantified by gravimetric measurements. Characterisations of certain coupons were performed by using µ-Raman and X-Ray Diffraction analyses. Chemical and microbial analyses of the water seepage were also performed.

Experimental set up

In situ corrosion experiments were conducted in a vertical descending borehole with a length of 12.31 m and a diameter of 350 mm (Figure 27). The borehole was drilled under aerated conditions down to - 9.45 m and under anoxic conditions from - 9.45 to - 12.31 m in order to prevent oxidation of the host rock. An experimental setup was then positioned at the borehole bottom (Figure 31). This setup was made by a test chamber initially containing synthetic clay pore water which was gradually replaced by water seeping from the clay during the experiment, and a gaseous atmosphere in contact with the water phase.

The test chamber was 558.5 mm high and contained seven inlets allowing the insertion and removal of rods supporting the test coupons. An in situ pressure sensor located at the base of the test chamber measures the total pressure (liquid + gas). The test chamber was surrounded by a filter tube in highly porous frit made of stainless steel to allow ingress of pore water. The test chamber was insulated from the gallery atmosphere by a packer inflated with water up to a pressure of 10 bars. Tightness was further improved by injecting resin in the outer annular space one week after packer inflation.

The test chamber was connected to a series of cabinets (a heating cabinet, a borehole water-monitoring cabinet, and a gas cabinet) located in the main shaft by a series of stainless steel lines. The heating cabinet was part of a heating system made of lines going through the central tubing of the apparatus for water heat-carrying liquid circulation, and by a tank in which a heat-carrying liquid was electrically heated gradually up to 100°C.

Thus the test chamber was heated to 85°C with a minimum temperature gradient in the vertical direction. The pressures of the packer and test chamber were controlled by a control unit connected to the test chamber, the borehole water monitoring cabinet, and the gas cabinet and apparatus. Borehole water flowed from the test chamber to the borehole water monitoring cabinet thanks to a pressure gradient (3 bars) between the gallery and the test chamber. The temperatures, pressures, pH, oxydo-reduction Eh potential (Eh), Ec electrical conductivity (Ec) and gas/liquid flowrates were continuously monitored by using appropriate sensors, via a data acquisition system.

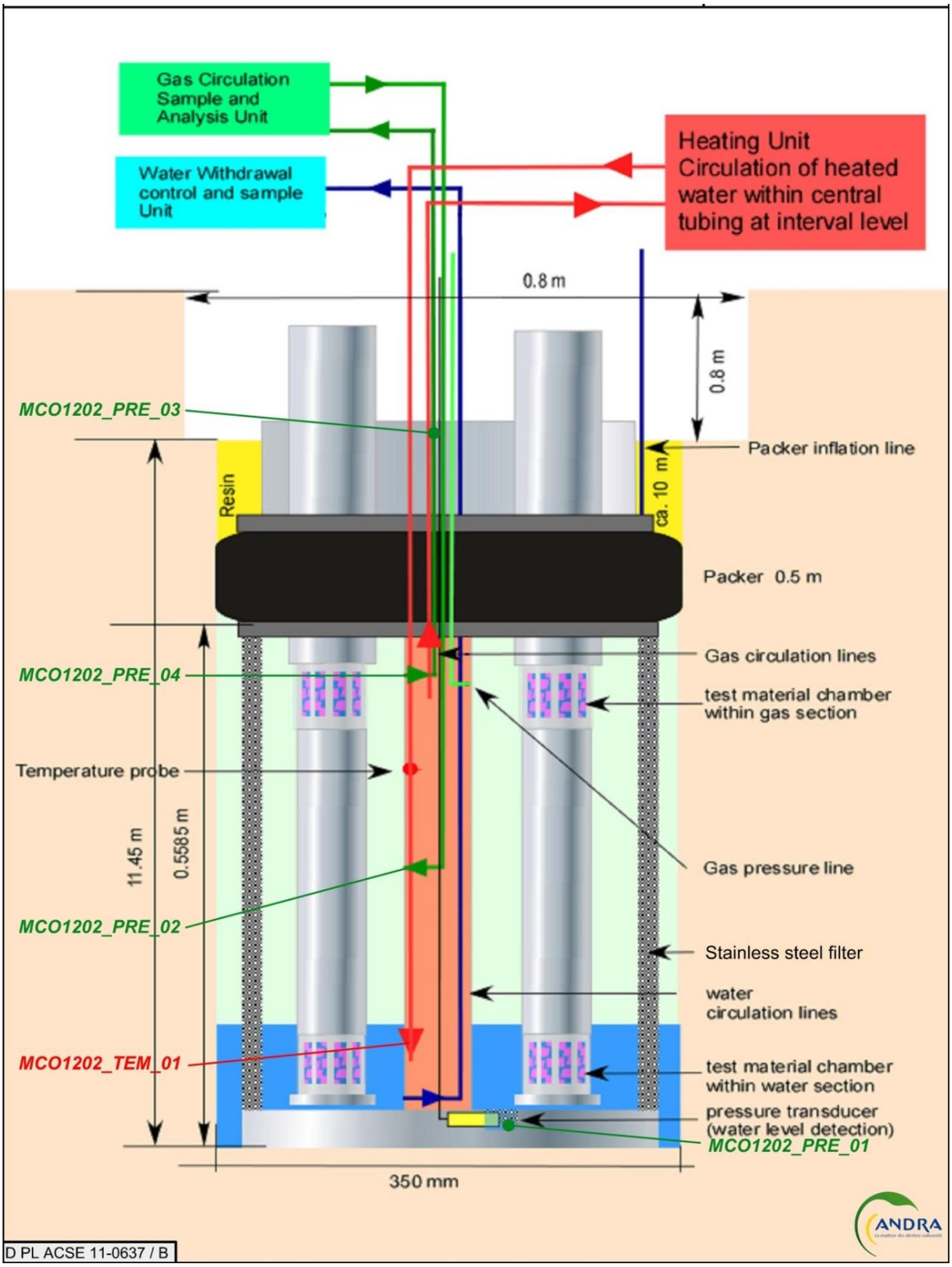

Figure 31 *MCO: Scheme of the experimental setup in the borehole*

Main results

One of the most challenging aspects of the MCO experiment was to keep control of temperature, pressure, gas composition, water level, air tightness; and solution chemical parameters in an in situ dual-phasic test chamber located at ~500 m underground, and for a period close to three years. Indeed, material failures may have unexpected consequences and can obscure corrosion results.

In spite of these difficulties, this study has brought forth crucial information and led to important constructive knowledge for the setup of deep repositories in clay host rock. The key points learnt from this work are as follows:

- The presence of an acidic transient was monitored and explained, and its consequences on the CR of C-steel in clay were observed;
- Non uniform general corrosion was observed in both, the liquid and gas phases;
- The CR in the borehole water is significantly more important than in the gas phase in equilibrium;
- The drilling phase enhances salts precipitation and results in an increase in the contents of species of species such as chloride and sulphate in pore water initially seeping in the borehole;
- The chloride content seemed to promote the formation of a Fe hydroxychloride compound. The exact role of this solid in the persistence of active corrosion at the metal surface of the coupons exposed to the acidic transient has to be clarified;
- Microbial activity was in the liquid phase was demonstrated; its impact on the corrosion processes has to be clarified.

Some of the processes observed here could be avoided by implementing additional precautions during experimental setup. For example, drying and oxidation at the borehole wall could be minimized by drilling under anoxic conditions using water-saturated N2 gas.

However, such precautions would be difficult to implement during the operational phase of cell drilling and emplacement of HLW. Bearing in mind these operational constraints, results led to the development of new procedures to mitigate the aqueous CR of C-steel. In order to buffer the acidic transient, an alkaline backfill material such as cement/bentonite is foreseen.

Such a filling will buffer the acidity released from clay and limit transport of dissolved elements to and from the steel surface. Development of this new concept has spurred a new research effort to investigate the corrosion of C-steel in this medium.

4.6 Activities in the URL 2015-2020: the Licensing Application

4.6.1 R&D Programmes

Andra is now close to the submission of the licence application and all the scientific information is considered sufficient to apply for a construction licence.

However, on one hand the review of the license application may last several years (4 or 5) and many scientific questions will be asked by scientific reviewers. On the other hand design and analysis of the results obtained in the URL will take also many years.

It should be recalled that R&D will not stop following successful implementation but should continue during the construction and operational phases. The same level of R&D effort will not be applied continuously; it will need to be adapted and re-prioritised as programmes and evaluation of these programmes progress. Therefore R&D efforts should be maintained to help build and maintain societal confidence in Cigéo

During this phase, Andra has already tested innovative construction means and support such as compressible arch segments (see 4.6.2). New machines to be use for large drift excavation and injection of bentonite cement grout between wall rock and extrados liner.

On the scientific matters Andra will continue the analysis of monitoring the rock properties of the Callovo-Oxfordian, excavation work and ventilation effect.

In the same way long term experiments of interactions between rock and materials (Cement/Iron/Glass) will provide additional information and will support safety files

Finally a large scale experiment, prefiguring a HLW cells section has already started in order to study THM behaviour of the rock on a large scale taking into account the behaviour of the liner, gas characterisation inside and outside the liner, and the effect of the bentonite cement grout.

The expected results will complement the knowledge acquired over three decades in the URL and is intended to prepare the R&D work to be carried out in the first phases of construction of the disposal facility.

The Figure 32 shows the URL at the beginning of 2019.

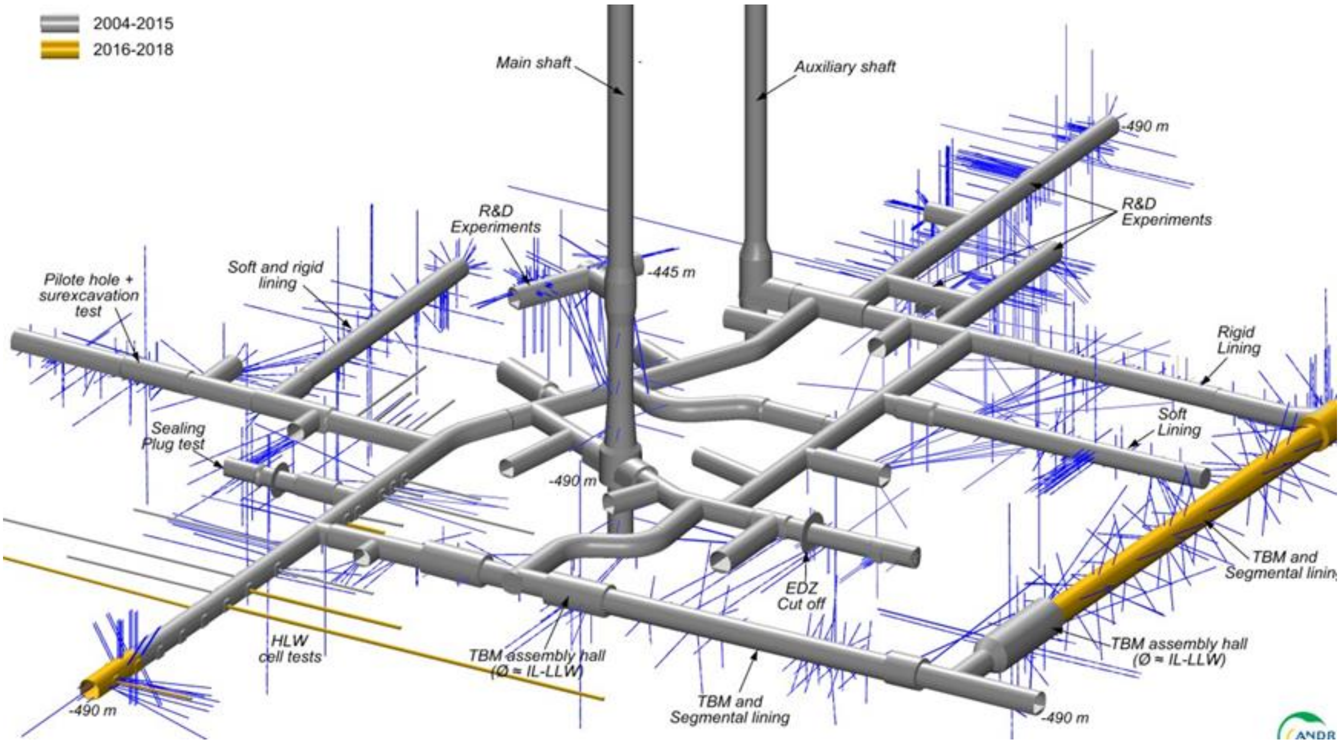

Figure 32 *Scheme of URL construction and experimental zones with new zones in operation during 2015-2019 (Yellow)*

4.6.2 GVA Experiment: Compressible Arch Segment test

Aims of the experiment

In the Cigéo concept IL-LLW vaults are oriented as per the major horizontal stress. That is why at the beginning most of the URL drifts were also oriented along the major horizontal stress (drifts GET, GCS, GCR, GRD, and GRM). As of 2015, drifts GER and GVA were/are excavated respectively with a road header technique and with a TBM technology. The new data collected will be compared to those initially acquired in the GED/GAN drifts and will provide the same level of knowledge for drifts parallel to the minor horizontal stress. The third portion of the GVA drift is the underground work in which the VMC "Compressible Arch Segment" technology was tested.

In addition, the URL offers a positive feedback concerning the behaviour of compressible elements already used in drifts experiments: compressible wedges (hiDCon®) embedded in shotcrete primary linings, and compressible grout (DeCoGrout/Compex) for segments lining backfill.

Lining monitoring confirms the impact of the compressible elements on the final support loading. Compressible elements capped the transmitted stress due to rock convergence as long as the compressible potential of the element is still active. This is why compressible elements can be a major benefit to optimize the final lining thickness.

VMC General Concept and benefits

The “Voussoir avec Matériaux Compressible” (VMC) invention relates to precast arch segments. It consists of adding a compressible layer on its extrados directly after pouring the reinforced concrete of the segment. Later on that compressible layer is protected by a thin layer of mortar. The positioning of the compressible layer aims to cap the radial stress due to the Callovo-Oxfordian convergence in the interface zone between the Callovo-Oxfordian and the reinforced concrete.

Figure 33 VMC prototype (left) and its compressible material coating (right) for GVA test drift

Figure 33 shows a prototype of a “VMC” compressible arch segment design for the final lining of the GVA drift. It is made of a regular reinforced concrete segment (some 43cm thick), coated (at the extrados) with some 13 cm of compressible material (called hereafter “shells”).

The shells are made of a ceramic material, produced from the host rock clay (Callovo-Oxfordian) excavated at the URL. The shells are ceramic, composed of baked crushed clay elements that are tube-shaped. Therefore, the void ratio of the material is increased. They are agglomerated (“glued”) by a cement grout offering an acceptable resistance for the workability and installation.

The strength of the VMC concept lies in:

- The added value by using excavated Callovo-Oxfordian to create shells;
- The chemical properties of the compressible layer: it is chemically inert and with no calorific load;
- The mechanical behaviour: shell’s dimensions and cement grout can be fitted in a way to follow the needed elastoplastic behaviour, first, an elastic behaviour to guarantee the integrity of the layer fabrication till erection followed by a compressible potential to cap the effect of the Callovo-Oxfordian convergence;
- The homogeneity in thickness, density and mechanical behaviour: as it is precast on surface, formulation, mixing, pouring and curing of that layer are properly controlled. Unlike the injected backfilled mortar, VMC concept guarantees the existence of a regular compressible layer, with the needed designed thickness, and with homogeneous properties. It is a significant advantage to VMC concept comparing to other technics, that’s why local radial loading on the extrados of the reinforced concrete segment is less likely.

GVA drift features

The first milestone in the validation of this construction solution as a potential optimization of Cigéo design was to integrate it into the construction planning of the drift GVA at the URL.

GVA drift parallel to the minor horizontal stress is a 120m long drift, excavated with a road header TBM with an outer diameter segment ring of 6 m and offering three different case study zones (40 m each). The first zone consists of backfilling the ring segment element with a classical mortar. The second zone is characterized by injecting a compressible mortar. The third zone uses the VMC elements. Excavation was done by Eiffage TP Company.

The TBM used for this experiment is a specific TBM manufactured by Herrenknecht with a road header (Figure 34). The machine have a rotary cutting head - Ø850 mm and a shield of 4 m length with 6, 27 m of diameter.

Figure 34 *Views of the TBM and digging*

A ring is composed of 9 segments precast on the factory of Stradal based in Maxilly-Sur-Saône - France. The main characteristics of the segments are the following:

- Dimensions: width = 0.80 m;
- Concrete = C75/60 (C0.65 1);
- Steel reinforcement ratio = 150 kg / m210(3 kg / m3 for the key segment);
- Segment reinforced concrete zone 45 : 2 & 1 cm; and
- Segment reinforced concrete zone 43 : 3 cm, with 13 cm of “shell compressible layer” and 2 cm of mortar cover layer.

The 13 cm thick layer of shells is enough for the experiment and the URL lifetime.

VMC rings implementation in GVA drift

The VMC rings were laid on the GVA drift between 20th of September and 12th of December 2017 (similar to the progress of the classical rings). The “non-industrial” advancement, compared to a conventional underground construction, is due to the different necessary requirements on the underground laboratory (limited number of persons, security requirements, weight, and volume limitations, aeration and cooling systems). The laboratory requirements (shaft sizes and maximum weight limitation) also affected the TBM design, in particular the capability of steering it in a way to closely follow the theoretical direction.

Finally the VMC ring installation was a success; VMC elements were transported (Figure 35), and installed without any significant problem (Figure 36).

Figure 35 *URL storage zone of VMC elements*

Figure 36 VMC ring installation

Experience gained

The fabrication of the compressible arch segments VMC proved to be feasible and adaptable to industrial production. Homogeneity of the shells and elastoplastic behaviour of the layer were confirmed.

The GVA experiment confirmed the technical feasibility of setting "Compressible Arch Segments" in a real excavation test with a TBM, and permits to gain a feedback in various operational situations.

The monitoring and analysis of the structure/rock interference will be followed in time. The global data analysis, will permit to verify, compares and estimates the reduction of the loading applied by the host rock and to the damping capacity of the VMC segments. Micro and macro mechanical modelling methods are being develop to correctly describe the VMC behaviour, and estimate the long term behaviour.

5. Overall View of the Experimental Programmes

5.1 Current List of Experiments Carried out from 1999 to Date

	Experiment	Objectives	Start	Location
ACC	Seismic waves experiment	Assessment of attenuation of seismic movements in depth by setting up accelerometers in shafts and drifts	2008	surface, shaft, drift at 445m and 490m
AHA	HLW disposal cell/liner behaviour	Demonstrate the technological feasibility of HLW construction in accordance with 2015 concept Obtain data on liner mechanical behaviour Test long term monitoring devices	2016	GAN
ALC	HLW disposal cell construction phase 1	HLW constructability (microtunelling pilot hole) HLW cell liner mechanical behaviour without and with thermal load Assessment of THM rock behaviour	2009	GRM
	HLW disposal cell construction phase 1 bis		2010	GAN

	Experiment	Objectives	Start	Location
	HLW disposal cell construction phase 2	around HLW cell Assessment of gas exchanges between HLW cell and the rock mass	2010	GAN
	HLW disposal cell construction Phase 3.1 (Heater test) (**HAC**)		2012	GAN
	HLW disposal cell construction ALC3004 (Gas) (**HAG**)		2012	GRM
	HLW disposal cell construction ALC3002 (Gas) (**HAG**)		2012	GRM
	Pilot holes for HLW cell		2013	GCR
BAC	Microbiological disturbances	Characterize impact of bacterial activity created by human activity and drift ventilation. Characterize the microorganism embedded in the rock mass	2009	GED
BBP	Low pH concrete test	Test of various type of low pH concrete formula - Assessment of their industrial feasibility Assessment of the durability and chemical stability at the rock contact Assessment of the THM characteristics	2014	GAN
BHN	Hydrated bentonite behaviour	Follow up natural watering of a bentonite plug directly in contact with HL cell wall	2014	GAN
BPE	Shotcrete layers as support	Assessment of the technical feasibility and performance of a thick (40 cm) shotcrete support	2012	GRD
CAC	HLW cells and sleeves behaviour	Assessment of the watering velocity of a HLW cell rock /liner annulus - assessment of the influence of the liner mechanical behaviour ; Test of an optical fibre in order to follow up THM liner behaviour Provide additional data on THM liner behaviour Assessment of 40m liner behaviour under mechanical loading	2010	GMR/GED/GEX/GAN/GCS
CCC	Compressible blocks behaviour at galleries crossing	Follow up complex structures behaviour lined with compressible blocks and supported by shotcrete	2015	Carrefour GVA/GCR
CDZ	EDZ compression behaviour	Test effect of confining pressure on drift wall mimicking bentonite clay swelling Test effect of deconfining after support breakdown	2011	GET

	Experiment	Objectives	Start	Location
DCN	Steel rib removal test	Removal of the steel rib and follow up of drift wall behaviour and fracturing	2014	Niche -445m
DIR	RN diffusion test n°1	Assessment of diffusion and retention parameter through in situ injection of tracers	2005	Niche -445m / GEX
DPC	Two phases construction test	Drift construction in two phases (two diameters) in order to check if EDZ extension could be reduced	2013	GRM
DRN	RN diffusion test n°2	Assessment of diffusion and retention parameter through in situ injection of tracers Assessment of vertical diffusion (anisotropy) Use of actinides as tracers	2011	NED
EPT	Pore water chemistry with temperature	Assessment of pore water composition evolution under a thermal load of 85°C	2012	NED
ERA	Filling liner/rock annulus of an HLW cell	Technical feasibility of annulus filling - assessment of mechanical performance	2013	GAN
FRO	Effect of oxidized rock on pore water composition	Study pore water composition evolution at the contact with drift wall subject to oxidizing due to ventilation	2014	GEX
FSS	Full Scale Sealing	Technical feasibility of a bentonite pellet plug at real scale with low pH concrete formulas	2013	Saint Dizier
GGD	Large diameter drift test	Assessment of the mechanical behaviour or an IL-LLW disposal cell	2012	GRD/GVA
GIS	In situ geotechnical measurements	Geo mechanical properties measurement in boreholes	2005	URL
KEY	EDZ cut-off experiment (180°) test n°1	Technical feasibility of slots - Technical feasibility of slot filling with bentonite	2005	GKE
MAG	Chemical interaction between rock an filling material	Assessment of the HLW cell annulus filling material	2018	URL
MCC	Metal corrosion in contact with concrete materials	Study metal corrosion under stress. Evolution of the stress field around metal ribs cast in a concrete block.	2016	GCS
MCO	Metal corrosion	Corrosion kinetics in various thermal conditions	2009	GMR/GED/GET /GCS/GRM
MHS	Surface hydrogeological survey	Long term head measurement monitoring of all aquifer formations below and under the Callovo-Oxfordian layer	2011	Surface
MLH	Chemical interaction between rock and concrete	Assessment of · chemical interaction clay rock/ lining concrete; · effect of environmental conditions (temperature hygrometry) on lining concrete evolution and concrete waste packages for IL-LLW.	2009	GED

	Experiment	Objectives	Start	Location
MVE	Vitrified waste behaviour	Dissolution kinetics in various thermal conditions	2009	GED
NSC	Real scale sealing plug	Performance assessment of a sealing plug at a scale close to real	2012	GCS/GES
NIH	Slanted bentonite sealing plug	Improve knowledge of sealing plugs behaviour in slanted boreholes	2016	Niche -445m
OHZ	EDZ survey	Follow up EDZ inception and long term evolution along drifts and cells	2008	all URL
ORS	Lining and support observations	Lining and support survey and in particular: follow-up mechanical load, fracture inception and evolution ; follow up of lining and support behaviour Develop monitoring and survey devices for IL-LLW cells	2010	GCR/GER/GCS/GRD
PAC	Pore water chemistry	Pore water composition in clay rock - effects of disposal disturbances on pore water composition - pore water CO_2 equilibrium	2005	GMR/GKE
PEP	Permeability measurements	Assessment of pressure head at distance of drift walls. Permeability tests in natural and disturbed conditions. Assessment of factors influencing the permeability.	2005	all URL
PGZ	HM disturbances created by gas	Assessment of gas pressure threshold - assessment of gas transfer in geological media and through plugs and seals	2009	GMR/GED/GEX
POX	Oxygen disturbance	Assessment of oxygen disturbances at the drift wall and potential consequences on pore water composition and retention properties	2009	GED
REM	Bentonite block watering	Bentonite block watering at large (1 cubic meter) scale	2014	Technological Centre
REP	Shaft mine by test	Follow up hydro mechanical response of clay rock during and after shaft excavation	2004	Niche 445m
RES	Regional seismic survey	Running and operation of a regional seismic network to assess natural conditions	2008	Surface
SDZ	EDZ under saturation and dewatering	Assessment of EDZ evolution under controlled hygrometry	2008	GED
SUG	Drift geological survey	Geological survey including EDZ inception and development under all excavation conditions	2004	all URL
TEC	Lining plastic deformation	Assessment of condition for liner deformation under thermal and mechanical stress	2010	GED
TED	Heater experiment 2	Heater experiment ; Assessment of THM properties of the rock under controlled thermal stress created by three thermal elements	2008	GEX

	Experiment	Objectives	Start	Location
TER	Heater experiment 1	Assessment of thermal intrinsic properties of the rock	2005	GKE/GEX
TPV	Tunnel boring machine	Technical feasibility of tunnel boring machine with segment erector. Segments are compressible – (GVA)	2012	GRD/GVA
TSF	Wireless transmission	Wireless transmission (electromagnetic waves) between two boreholes	2007	GEX
TSS	Slot tests	Technical feasibility of a slot 360°-follow up of its behaviour for 2 years	2010	GET

5.2 Selected List 'Experiment Record Sheet" by Cigéo Components

In Appendix is presented the experiment record sheet of 6 experiments, each of them representing a Cigéo component

5.2.1 Component: The General Geological Features: DIR Experiment

DIR Experiment is, for the clay concept, the first and the most important experiment to assess the containment properties of the host rock and to provide parameters for regional diffusion fluxes through the layer.

5.2.2 HLW Component: ALC Experiments

ALC Experiments were the first tests preparing at real scale what could be the waste emplacement for HLW and its interactions with the host rock. This first experiment paved the way to many others. To date 20 HLW horizontal cells have been drilled and instrumented.

5.2.3 IL-LLW Component: TPV Experiment

A tunnel boring machine was specifically built for Andra purposes in the URL. The machine is a road header protected by a shield and have a segment fitter. Non-compressible and compressible segments have been installed. Grouting injection was performed in some parts of the drift to fill the gap between the segments and the rock. Two main drifts have been drilled on in a direction parallel to the maximum horizontal stress, the other perpendicular to this direction.

5.2.4 Closure Components: NSC Experiment

NSC was one of the most complex experiment carried out in the URL. Its design took more than five years. This experiment prefigured what could be a sealing used in the disposal.

5.2.5 Full-Scale Repository: MVE Experiment

This component comprises the knowledge of the geological settings as well as the development of numerical simulation related to their evolution. Amongst the experiments those dealing with rock material interaction are of great importance. The MVE experiment aims at assessing glass dissolution kinetics in various thermal conditions.

5.2.6 Environmental Monitoring, Observation/Surveillance and Human and Social Sciences: RES Experiment

For long term safety purpose, but also for building design safety options, the seismological context had to be studied in depth. Andra has installed in collaboration with the French Atomic Energy and Alternative Energies Commission (CEA). A network of seismograph. The experiment record sheet presents the main features of the seismological context.

ANNEX 1

DIR EXPERIMENT

Experiment acronym / description		DIR	“**D**iffusion of **I**nert and **R**eactive tracers”		
Type	☒ Scientific ☐ Technological	**Component(s)**	Geological and hydrogeological medium	**Sub-Component(s)**	COX
Topic		Transport of RNs and toxic elements			
Cigéo life phase		☐ Operation ☒ Post-closure 0 10^1 10^2 10^3 10^4 10^5 ans		**Level in the Callovo-Oxfordian**	☒ UA ☒ USC

LOCATION

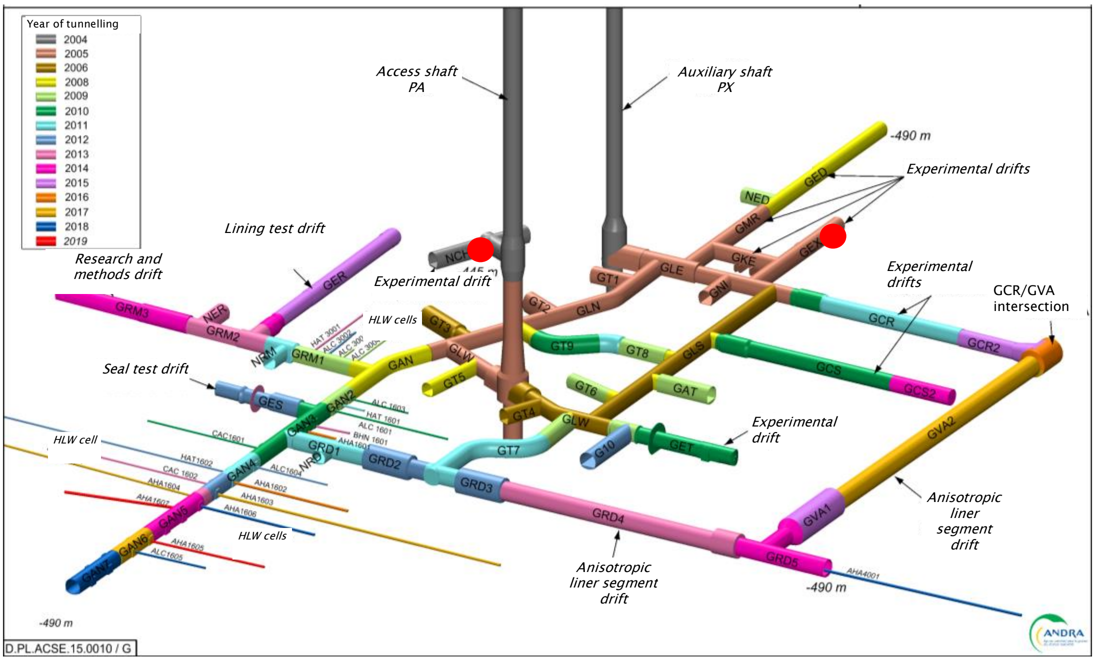

Figure 1 *Andra’s URL layout*

EXPERIMENT OBJECTIVE(S)

In-situ measurement of diffusion parameters: diffusion coefficients, anisotropy, accessible porosity and retention parameters:

- Over distances ranging from a few centimetres to several decimetres;
- For three types of solutes: inert species (e.g. tritium [HTO]), anions that undergo anionic exclusion and cations that interact with the rock by sorption;
- For the different rock types found in the Callovo-Oxfordian layer (clay unit (UA) and silty-carbonated unit (USC)).

Start date: January 2005	Duration: Short- to medium-term	End date: 2006 to 2009

PRINCIPLE

The experiment entails putting water containing various “tracers” into contact with the rock using an injection chamber comprising a borehole section closed with a water inflatable packer system (Figure 1). The water circulates in a closed loop between the injection chamber and a tracer injection and water sampling cabinet in the drift. The chamber is located far enough from the drift to ensure that the test takes place in a water-saturated zone outside the area potentially damaged by tunnelling. For operational reasons, such as the technical feasibility of overcoring following the test, the injection chamber is vertical in a downward direction and highly elongated. The tracers consequently migrate from the injection chamber through the Callovo-Oxfordian clay-rich rock as a diffusive flux, chiefly in a radial direction, parallel to the rock strata.

In order to minimise disruptive effects, (i) hydrostatic pressure in the test space is kept at the local pressure level of the rock formation, to prevent transfer by advection, and (ii) the composition of the solution containing the tracers is close to that of the rock pore water.

Following injection of the tracer cocktail into the injection system, the concentration of each tracer is monitored over time over a period ranging from 100 to over 1000 days. At the end of this phase, the rock volume in which the tracers were found to have diffused is removed using large-diameter core sampling (350mm diameter, whereas the injection chamber diameter is 76mm) and the tracer concentration profiles in the rock are measured in several directions from the injection chamber.

Specific numerical models are used to interpret the data acquired (decline in tracer concentration in the injection chamber, concentration profiles in the rock, anisotropy of transport parameters measured in samples taken close to the experimental borehole, etc.) and hence to deduce the diffusion parameters. Direct trial-and-error modelling or reverse models are used to optimise the diffusive transfer parameters for the tracers and identify any spatial variation.

EXPERIMENTAL PROTOCOL and DESIGN

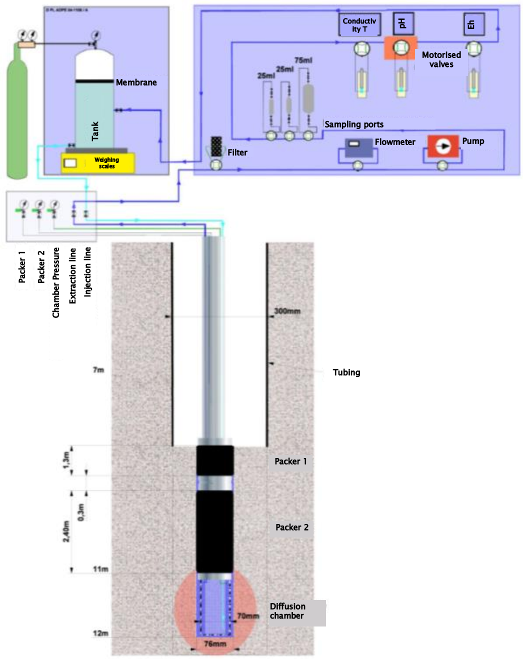

Figure 2 *Schematic diagram of the tracer injection tests for DIR experiments in the Underground Laboratory*

PARAMETER(S) MEASURED and NUMBER OF MEASUREMENTS ACQUIRED

Seven tests were performed: six in the Underground Laboratory and one from the surface (Dewonck, 2010):

- Tests DIR2001, DIR2002 and DIR2003 from the experimental drift located at level -445m in the silty-carbonated unit (USC).
- Tests DIR1001, DIR1002 and DIR1003 from the experimental drift located at level -490m in the clay unit (UA).
- One test from the surface level using deep borehole EST208 down to a depth of 540m.

The following elements were injected:

- One non-interactive reference molecule: tritiated water (HTO);
- Anionic species: chlorine, iodine, (non-radioactive) bromine, selenium (Se(IV)) and niobium (non-radioactive Nb(V))
- Cations: cesium (Cs^+), sodium (Na^+), strontium (Sr^{2+}) and cobalt (non-radioactive Co^{2+})

Some tracers (Cs, I, Se) were injected with a stable carrier in order to limit retardation from chemical retention (sorption site saturation effect). Another group of tracers (Nb, Cs, Co) was injected in stable form with the aim of using them as a functional test. The test conditions are summarized below (Table 1).

Table 1 *DIR tests: Rock types and tracers*

Boreholes	Rock type	Anionic tracers	Water tracers	Cationic tracers
DIR2001		○ $^{36}Cl^-$ ○ $^{125}I^-$ with carrier	HTO	-
DIR2002	C2b2	-	HTO	○ $^{22}Na^+$ ○ $^{134}Cs^+$ with carrier
DIR2003		$^{36}Cl^-$	HTO	○ $^{22}Na^+$ ○ $^{134}Cs^+$ with carrier
DIR1001		-	HTO	-
DIR1002	C2b1	-	HTO	○ $^{22}Na^+$ ○ $^{85}Sr^{2+}$ ○ $^{134}Cs^+$ with carrier
DIR1003		○ $^{75}SeO_3^{2-}$ with carrier ○ $^{125}I^-$ with carrier then without ○ Br^-	HTO	-
EST208	C2a	$^{36}Cl^-$	HTO	$^{134}Cs^+$ with carrier

Tracer activity monitoring in DIR test fluids

Following tracer injection, samples were taken regularly in the injection system in order to monitor tracer concentration (Blin *et al.*, 2010a). Figure 3 illustrates the variation in C/C_0 relative tracer concentrations ($C_{measured}/C_{injected}$) in the fluid circulating in boreholes DIR1002 and DIR2003 from tracer injection until the test was disassembled (Dewonck 2010). Compared with reference tracer HTO, the concentrations of cationic species ($^{22}Na^+$, $^{85}Sr^{2+}$ et $^{134}Cs^+$) drop quicker in the fluid, and the concentration of the anion ^{36}Cl falls more slowly. The behaviour of the cations can be explained by the differences in retention properties: $Kd(Na^+) < Kd(Sr^{2+}) < Kd(Cs^+)$; distribution coefficients Kd were used to describe retention (Andra, 2018). With respect to the anion, anionic exclusion reduces its accessible porosity compared to HTO. As well as tracer monitoring, the major ions were also analysed.

Tracer concentration fell quickly in the days immediately after injection; this drop occurred quicker than in the predictive models, which had been based on a spatially-uniform diffusion coefficient. This rapid drop is due to the presence of a zone of disturbed rock around the boreholes, through which the tracers diffuse more quickly than in undamaged rock. The presence of this zone was subsequently taken into account in test interpretation.

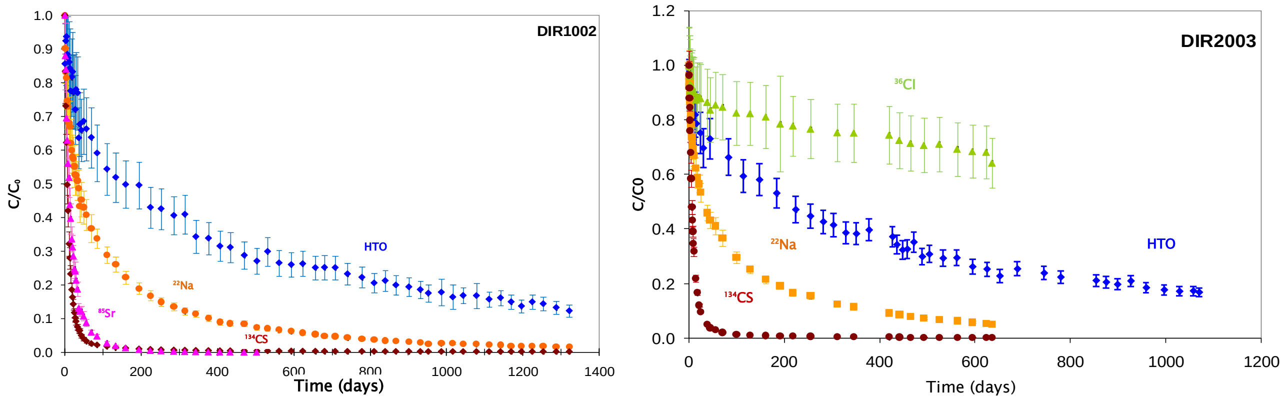

Figure 3 *Variation over time in relative concentration of HTO, $^{22}Na^+$, $^{85}Sr^2$ and ^{134}Cs in borehole DIR1002 (left) and relative concentration of ^{36}Cl, HTO, $^{22}Na^+$ and $^{134}Cs^+$ in borehole DIR2003 (right)*

Disassembly, overcoring and diffusion profiles

Following the fluid monitoring period, the equipment was flushed out and the packer system removed. The holes left when the packer systems were removed were resin-filled. The rock volumes in which the tracers had diffused were then extracted by core drilling (Table 2). The large-diameter core sample from this overcoring was then sub-sampled; Tracer concentration was measured in each sub-sample to determine concentration profiles for each tracer, starting from the test chamber wall and running in different directions (cf. (e.g.) Blin *et al.*, 2010a 2010b, 2010c for boreholes DIR1001, DIR1002 and DIR1003). Cesium specific activity profiles around experiment

DIR1002 are presented in **Erreur ! Source du renvoi introuvable.**. It should be noted that tracer profiles were not acquired for borehole E ST208, where overcoring was not performed.

Table 2 Test disassembly dates

	Flushing	Equipment withdrawal	Overcoring
DIR2001	30 January 2006	30 January 2006	29 January 2009
DIR2002	1 February 2006	1 February 2006	16 February 2006
DIR2003	9 June 2008	June 2008	15 January 2009
DIR1001	23 September 2009	23 October 2009	19 November 2009
DIR1002	22 September 2009	23 September 2009	7 October 2009
DIR1003	21 September 2009	22 September 2009	30 September 2009

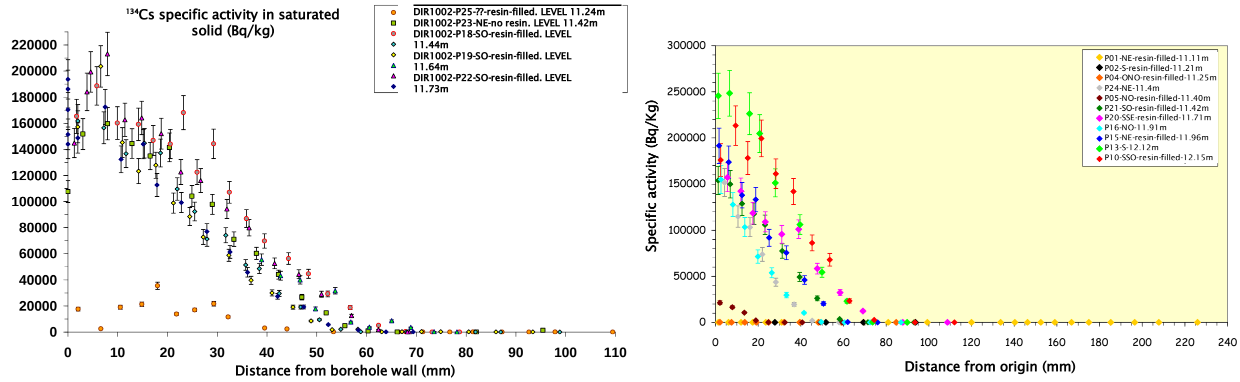

Figure 4 *^{134}Cs specific activity in the solid profiles from borehole DIR1002 tested by the CEA (left) and Subatech (right), by distance from borehole wall (injection chamber)*

Analysis of these profiles shows:

- That the mass balances are incomplete for some tracers (^{22}Na and HTO in particular). These tracers diffused further than the overcored volumes (10.7cm from the injection chamber);
- The activity values are generally consistent for all tracers in the majority of profiles analysed. However, the profiles from the top of the injection chambers show lower levels of activity or no activity;
- That the diffusive regime was disrupted for boreholes DIR2001 and DIR2003. This is explained by the fact that DIR2001was overcored 3 years after the injection equipment had been withdrawn and DIR2003 was left for 220 days at atmospheric pressure, which allowed a centripetal advective transfer.

<u>Interpretive models</u>

Tracer diffusion was modelled from the decreasing tracer concentration monitoring in the injection system and the concentration profiles around the injection chambers (Filippi and Blin, 2010). Two approaches were used to interpret the test results: a "transport"-type approach, which took retention into account using K_d or isotherms (for cesium only) and a "chemical-transfer"-type approach (using PHREEQC software) that incorporated the following geochemical processes: solubility, speciation, cationic exchange.

The modelling considered (i) an axisymmetric system geometry comprising the injection chamber, a disturbed zone (with modified transport properties) and undamaged rock, (ii) an anisotropic diffusion tensor in the undamaged rock, (iii) the specific history of each borehole, including any periods of latency between the end of injection and measurement of the concentration profiles.

The modelling outputs showed that:

- The diffusion profiles from boreholes at the -490m level are the only ones that show diffusive behaviour. The history of the boreholes at the -445m level is too complex, due to the events that occurred during the injection period. The parameters deduced from the tests at -445m thus come with greater degrees of uncertainty.

- The in-situ test results are generally consistent with knowledge of Callovo-Oxfordian rock obtained on rock core samples. Just as for hydrodynamic tests, it is necessary to take into account a disturbed zone of approximately 2-3cm around each borehole in order to explain diffusion results.

PRINCIPAL RESULTS and LESSONS LEARNED

PRINCIPAL RESULTS

Table 3 presents the diffusion parameters obtained in this experiment. There is good agreement between range of effective diffusion coefficient values for HTO, chlorine, iodine, bromine, sodium and cesium and measurements obtained on core rock samples, if anion exclusion and cation acceleration are taken into account. Of the cations, the cesium showed an effective diffusion coefficient greater than that of the sodium; this behaviour also agrees with measurements obtained on core rock samples by through-diffusion experiments. The sodium and cesium retention parameters are consistent with the values obtained through batch tests (Andra, 2018).

Table 3 *Diffusion parameters obtained by modelling of the DIR tests, and comparison with parameters derived from laboratory tests on rock samples*

Tracer	DIR200X C2b2 De (10^{-12} m²/s)	DIR100X C2b1 De (10^{-12} m²/s)	EST208* C2a De (10^{-12} m²/s)	Callovo-Oxfordian Sample De (10^{-12} m²/s)
HTO	$35 \le De_R \le 49$ $14\% \le \omega \le 17\%$ $De_Z = 27$ $\omega = 20\%$	$35 \le De_R \le 60$ $14\% \le \omega \le 17\%$ $27 \le De_Z \le 36$ $13\% \le \omega \le 15\%$	$De_R = 41$ $\omega = 18\%$ $De_Z = 22$ $\omega = 18\%$	$31 \le De_R \le 47$ $15\% \le \omega \le 23\%$ $20 \le De_Z \le 37$ $18\% \le \omega \le 22\%$
Anions	$2.5 \le De_R \le 2.7$ $\omega = 5\%$	$5 \le De_R \le 8$ $4\% \le \omega \le 8.5\%$	$De_R = 7.8$ $\omega = 9\%$	$5{,}2 \le De_R \le 9.0$ $6\% \le \omega \le 8\%$ $5{,}1 \le De_Z \le 8.8$ $8\% \le \omega \le 12\%$
Cation ^{22}Na	$De_R = 100$ $\omega = 18\%$ $K_d = 0.74$ L.Kg^{-1} $De_Z = 66$ $\omega = 18\%$ $K_d = 0.74$ L.Kg^{-1}	$110 \le De_R \le 200$ $\omega = 18\%$ $K_d = 0.65$ L,Kg^{-1} $79 \le De_Z \le 132$ $\omega = 18\%$ $K_d = 0.65$ L.Kg^{-1}	-	$62 \le De_R \le 95$ $0{,}7 \le \omega R \le 0.8$ $K_d = 0.3$L.Kg^{-1} $42 \le De_Z \le 64$ $0{,}8 \le \omega R \le 0.9$ $K_d = 0.3$L.Kg^{-1}
Strong cation ^{134}Cs	$De_R = 190$ $\omega = 18\%$ $K_d = 21$ L.Kg^{-1}	$De_R = 44$ Langmuir isotherm	-	-

*For EST208, the results are derived solely from fluid monitoring, since the borehole was not overcored

De_R: effective radial diffusion coefficient in the mid-height plane perpendicular to the borehole;

De_Z: effective axial diffusion coefficient perpendicular to the mid-height plane;

ω: porosity;

K_d: distribution coefficient.

Modelling-based interpretation was not used for certain tracers:

- The diffusive behaviour of the selenium (Se(IV)) could not be interpreted because its concentration had fallen very quickly in the injection chamber after only a few days. This observation could be explained by precipitation through reduction of the selenite ions (SeO_3^{2-}) into selenium in elementary form (Se^0).
- Qualitative interpretation was the only approach used for Nb behaviour (injected only in EST208), since the concentration in the injection chamber fell too quickly (approximately one day). This rapid drop, quicker than for Cs is in agreement with the high retention properties expected for Nb (V).
- Since Sr was injected in the form of ^{85}Sr (half-life of 65 days), the Sr profile could not be determined.

PRINCIPAL LESSONS LEARNED

- The concept of a disturbed zone had to be introduced when the DIR tests were modelled. Schematically, this zone was modelled as a rock annulus, 1 to 3cm thick, around the diffusion chamber, with higher diffusion parameters than in the undamaged rock.
- The experimental principle used in the DIR test required diffusion distances ranging from a few centimetres to several decimetres, with maximum durations of a few years. Other methods need to be used to study in-situ diffusion over longer durations and longer distances. This is the focus of the DRN experiment.

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ANNEX 2

ALC Experiment

Experiment acronym – Name		ALC	HLW disposal cell and sleeve		
Type	☒ Scientific ☒ Technological	Component(s)	HLW disposal section	Sub-Component(s)	Cell, Sleeve, Damaged zone
Topic		Technological feasibility and HM behaviour			
Cigeo life phase		☒ Operation ☐ Post-closure		Level in the Callovo-Oxfordian	☒ UA ☐ USC

LOCATION

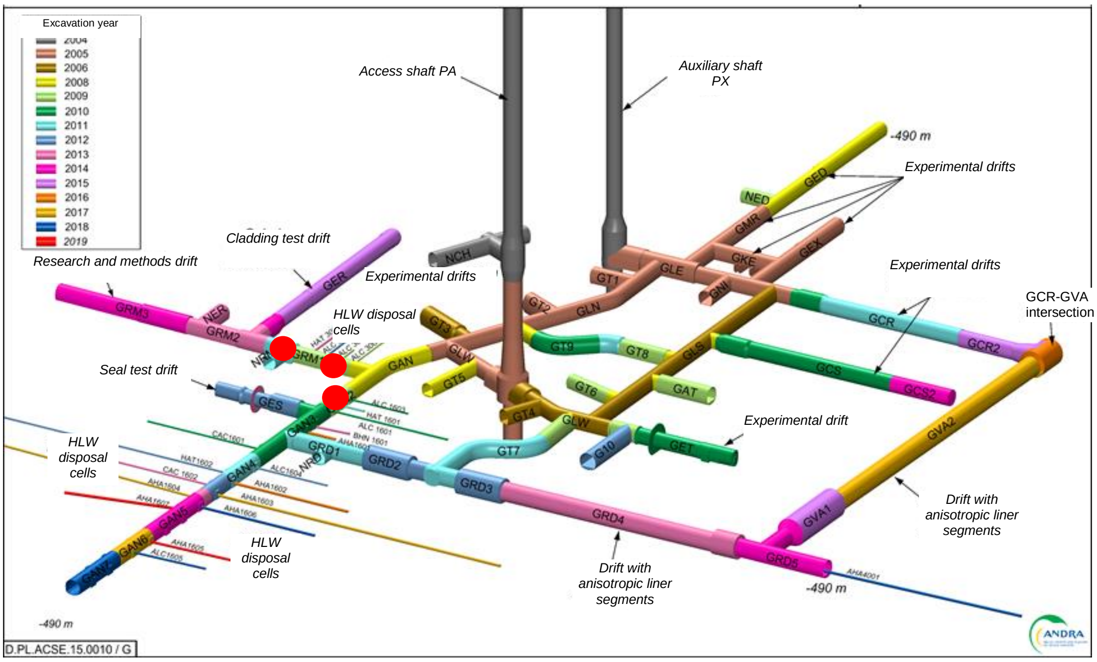

Figure 1)Location of the 6 ALC experiment cells (drifts GRM1 and GAN2)

EXPERIMENT OBJECTIVE(S)

- **Test the feasibility of construction of an HLW cell conforming to the 2009 concept (i.e. without filling the annular space):**
  - ✓ **Test the feasibility of excavating a microtunnel and installing the sleeve in various directions with respect to the stress field in situ;**
- **Acquire data on the hydromechanical (HM) behaviour of HLW cells:**
  - ✓ **HM impact on the surrounding rock of excavation of a cell;**
  - ✓ **Mechanical behaviour of the cell (convergence);**
  - ✓ **Damage generated around the structure by the excavation.**

Start date: 2009	Duration: Long-term	End date:

PRINCIPLE

The principle of the experiment is to demonstrate the construction of an HLW disposal cell 40 metres long, representative of the 2009 concept (refer to C.NSY.ASTE.08. 0429.A).

The ALC experiment involves the excavation of six cells with objectives that are both technological (demonstration of the feasibility of the excavation and of the installation of a sleeve) and scientific (short- and long-term hydromechanical response to microtunnel excavation). The cells were excavated consecutively to increasing lengths for ultimate demonstration of the possibility of reaching 40 m (reference length of the 2009 concept).

Microtunnels were excavated in various orientations with respect to the stress field in situ (σ_H and σ_h) with or without installation of a steel sleeve. The main objectives of the unsleeved cells are scientific, to analyse the hydromechanical behaviour of the microtunnels during excavation and in the longer term (time-dependent behaviour), but they also have the technological objective of estimating the time allowable between excavation and sleeve installation.

EXPERIMENTAL PROTOCOL and DESIGN

The gradual extension of the disposal cell construction programme in various directions with respect to the stress field *in situ* (σ_H and σ_h) with or without installation of a steel sleeve has enabled optimisation of the technique for excavation and sleeve installation.

Given the feedback from experience with the excavation of larger drifts, pre-excavation pore pressure measurement (Mine-by-test) was implemented. Because of the size of the cells (diameter around 750 mm), for which the radial displacements around the cell were expected to be highly localised (proportional to 1/r with respect to the wall), no displacement measurements were made in the surrounding rock. Convergence measurements were made in unsleeved cells.

Geophysical measurements between the wall and nearby boreholes were tested for characterisation of the excavation-damaged zone.

Cell ALC3005 was over-excavated to obtain better understanding of the fracturing model generated by microtunnel excavation (in relation to the model determined for the drifts).

- **Instrumentation installed before structure excavation**

The following instrumentation was installed prior to cell excavation:

- ✓ 5 boreholes with hydrogeological packer systems for pore pressure measurement around the cells made in GRM1 (March 2009);
- ✓ 4 cased boreholes for the geophysical measurements around the unsleeved cells made in GRM1 (March 2009)[4];
- ✓ 5 boreholes with hydrogeological packer systems for pore pressure measurement around the cells made in GAN2 (February 2009);
- ✓ 1 cased borehole for the geophysical measurements around the unsleeved cell made in GAN2 (February 2010).

- **Cell construction in two phases**

  - ➢ <u>Phase 1 (drift GRM1)</u>

In phase 1, 4 cells were made in GRM1 in 2009 and 2012 (ALC3002):

- ✓ ALC3001: sleeved cell length 10 m parallel to σ_h, annular space 1 cm, spot-welded sections, excavation by 1 shift/day (from 29 April to 06 May 2009), blocked at 10 m;
- ✓ ALC3005: unsleeved cell length 20 m parallel to σ_H excavated at drift face, diameter 740 mm, excavation by 3 shifts/day (from 25 to 27 May 2009);
- ✓ ALC3004: sleeved cell length 20 m parallel to σ_h (ALC3004): annular space 2 cm, spot-welded sections, excavation by 3 shifts/day (from 22 to 25 June 2009);
- ✓ ALC3002: unsleeved cell length 20 m parallel to σ_h, diameter 750 mm (new machine), excavation by 3 shifts/day (from 6 to 8 November 2012).

  - ➢ <u>Phase 1a (drift GAN 2 – Figure 2)</u>

During phase 1a, 2 cells were made in GAN2 in 2010:

- ✓ ALC1601: sleeved cell length 40 m parallel to σ_H, annular space 2 cm, push-fit sleeve sections, excavation by 3 shifts/day (from 4 to 7 May 2010);
- ✓ ALC1603: unsleeved cell length 20 m parallel to σ_H, diameter 740 mm, excavation by 3 shifts/day (from 25 to 28 May 2010).

All the cells made are summarised in the table below.

Date	Cell	Orientation	Length (m)	$\varnothing_{excavation}$ (mm)	$\varnothing_{out\_sleeve}$ (mm)	Sleeve joints
04/2009	ALC3001	σ_h	10	720	700	Spot welding
05/2009	ALC3005	σ_H	20	740	-	Unsleeved

[4] Measurements finally not made due to inadequate cell wall quality.

06/2009	ALC3004	σ_h	20	740	700	Spot welding
05/2010	ALC1601	σ_H	40	740	700	Push-fit
05/2010	ALC1603	σ_H	20	740	-	Unsleeved
11/2012	ALC3002	σ_h	20	750	-	Unsleeved

All excavation was by microtunnel boring machine in the dry.

<u>The following parameters were measured during excavation</u>: forward speed, thrust forces on the drill and on the sleeve train, and torque applied to the cutting wheel.

- <u>Sleeve characteristics</u>

✓ installed as excavation progresses;
✓ S235 structural steel tubes $\varnothing_{inn}$ = 660 mm, $\varnothing_{out}$ = 700 mm, length = 2 m.

- **Experiment diagrams**

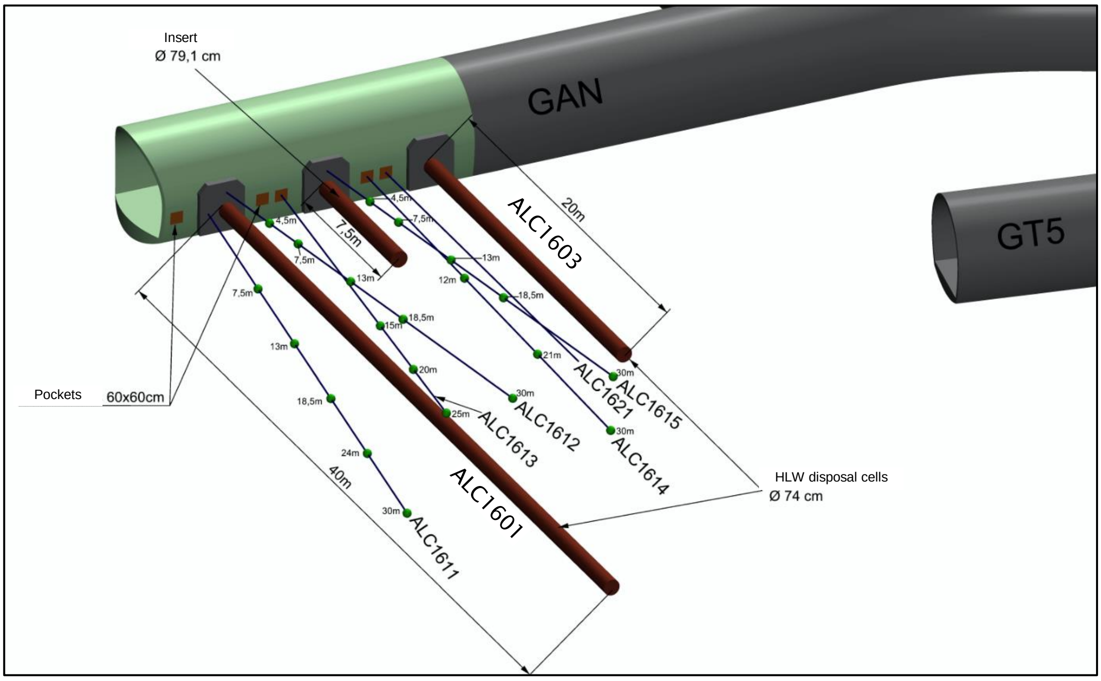

Figure 2 Boreholes and cells made in drift GAN2

- **Instrumentation installed after excavation of the structures**

✓ Recording of a 3D scan in all the unsleeved cells immediately after excavation[5];
✓ Installation of convergence measurement sections in the unsleeved cells (4 sections/cell at different distances from the access drift);
✓ Installation of a sensor probe for the geophysical measurements inside cell ALC1603.

MEASURED PARAMETER(S) and NUMBER OF MEASUREMENTS ACQUIRED

[5] A second 3D scan of cell ALC1603 was recorded 3 weeks after excavation to estimate the short-term convergence (before installation of the convergence measurement sections).

- Pore pressure in the rock;
- Cell wall displacement;
- Cell initial geometry;
- Excavation machine thrust forces and torque;
- Seismic wave propagation velocities for characterisation of the excavation-damaged zone.

PRINCIPAL RESULTS and LESSONS LEARNED

PRINCIPAL RESULTS

- **Construction technological feasibility**

After the blocking of the first cell excavated (ALC3001) at a depth of 10 m, mainly because the initial annular space was too narrow (1 cm), all the other cells of the series reached their target lengths, whether parallel to σ_H or to σ_h. In particular, a cell 40 m long (conforming to the 2009 concept) with sleeve installed as excavation progressed (cell ALC1601) was completed parallel to σ_H, despite loss of guidance after 20 m. The following parameters had to be adjusted in order to achieve this target:

- ✓ The initial annular space between the sleeve and the rock, which must be wide enough to avoid any risk of blocking in the rock, while nevertheless not compromising the control of the path and the straightness of the excavation.
- ✓ An initial annular space of 20 mm was found to be sufficient, the thrust force on the sleeves reaching 130 t at the end of the excavation (Figure 3);
- ✓ The rate of progress of the excavation, which must be continuous at a high enough speed to avoid any risk of blocking by convergence of the rock (the average speed was 0.55 m/h for ALC1601);
- ✓ The stiffness of the sleeve, which must not be too high, so that the sleeve can adapt to the actual path of the cell, which is not perfectly straight. This constraint led to the implementation of push-fit joints between the sleeve sections, starting in phase 1a.

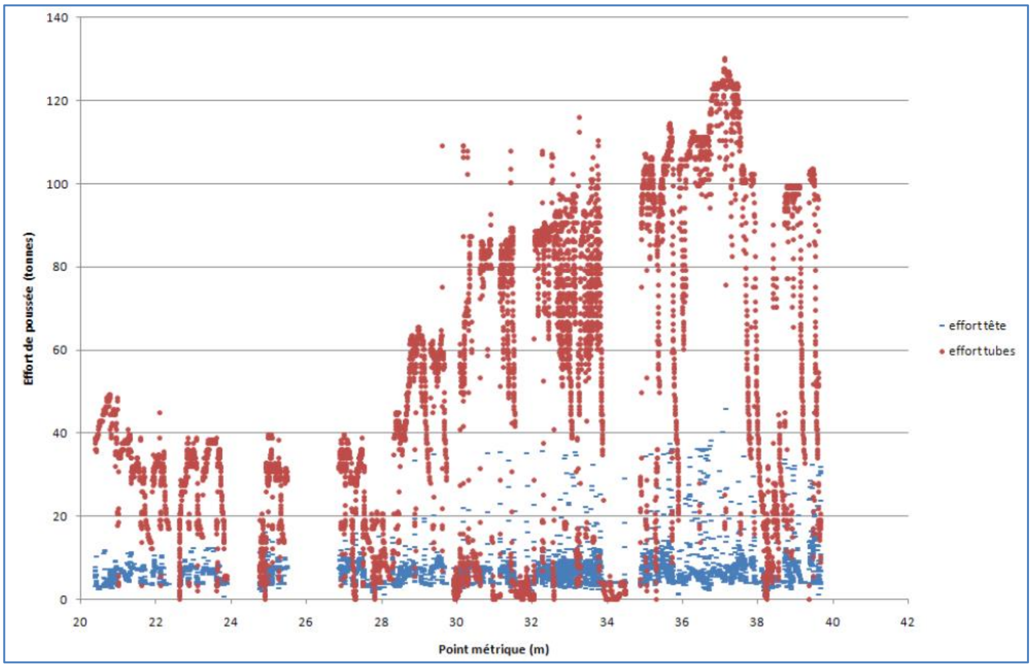

Figure 3 *Thrust force on the drill head and on the sleeve train (ALC1601)*

- **Hydromechanical response of the Callovo-Oxfordian**

  - ➢ Pore pressure profiles

The response of the pore pressure field around the cells to the excavation is anisotropic, whatever the orientation of the cell. This behaviour anisotropy, linked directly with the inherent mechanical anisotropy of the rock, is expressed as a pressure increase in the horizontal plane and a pressure reduction in the vertical plane. The measurements obtained in these two planes around cell ALC1601 are shown in Figure 4. The horizontal plane overpressure values are higher the closer the measurement chamber is to the cell wall. This behaviour is similar to that observed with larger-diameter structures (drifts).

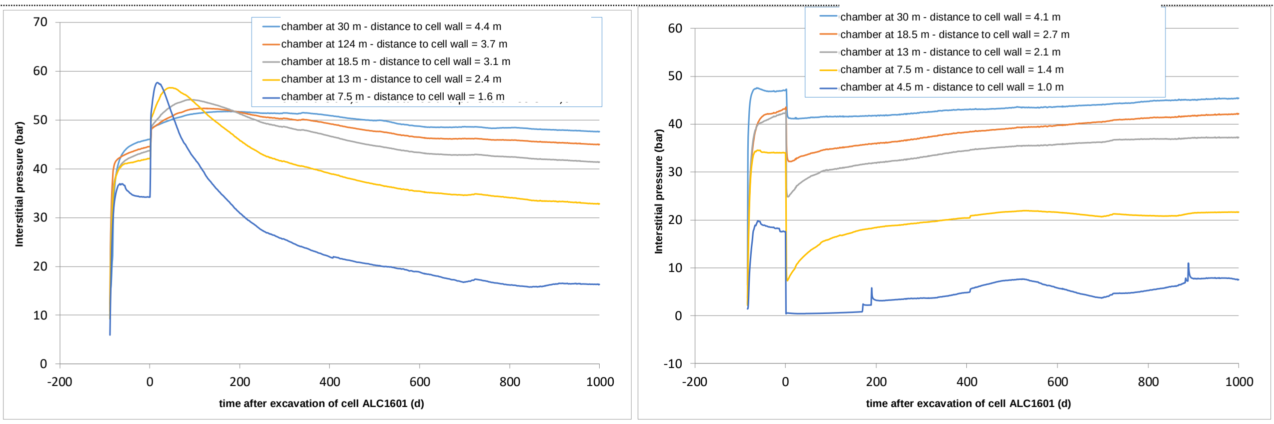

Figure 4 *Time course of pore pressure around cell ALC1601 – Measurements made in the horizontal plane (borehole ALC1611, left) and in the vertical plane (borehole ALC1612, right) and at different distances from the access drift and from the cell wall (see* ***Erreur ! Source du renvoi introuvable.****)*

➢ <u>Damage around the cell</u>

The 3D scans of the unsleeved cells show profile deviations of up to 100 mm, located mainly at 45° either side of the vertical axis (Figure 5). Cell ALC3002, oriented parallel with σ_h, shows profile deviations that are twice as large, because of the greater vertical extent of the damaged zone.

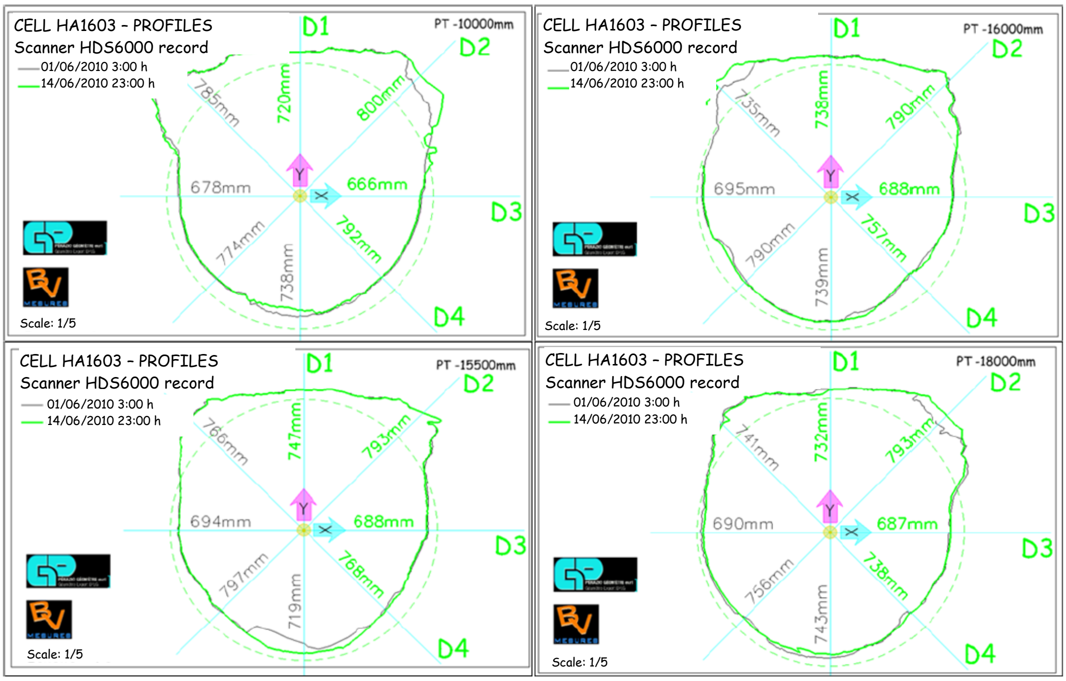

Figure 5 *Cell ALC1603 profile at different distances from the access drift (10, 15.5, 16 and 18 m) 3 days (grey) and 2 weeks (green) after excavation*

The geophysical measurements (P and S wave velocities, seismic refraction) made around cell ALC1603 in the 2 weeks following its excavation show damage anisotropy, as previously observed for larger-diameter structures excavated in the same direction (Figure 6).

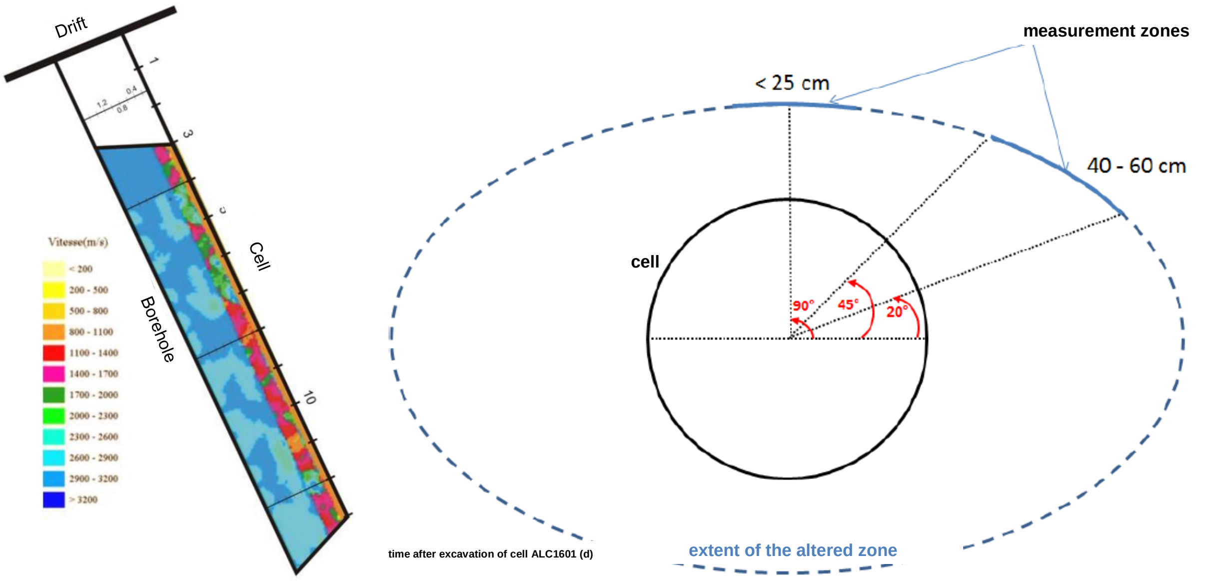

Figure 6 *Seismic tomography at the right facing of cell ALC1603 (left) – Schematic diagram of the zone showing velocities affected by the damage (right)*

The over-excavation of cell ALC3005 carried out when excavation of drift GRM was resumed in 2011 enabled observation of the fracture network around the cell (Figure 7). The network and the type of fractures are similar to those observed for drifts with the same orientation.

Figure 7 *Fracture network around cell ALC3005*

➢ Convergence

The anisotropy of the excavation damaged zone generates convergence anisotropy, as shown in Figure 8. For structures parallel to σ_H, the short-term (less than 2 years) convergence rate is markedly higher in the horizontal direction (direction of maximum extent of the damage) than in the vertical direction. The rates subsequently become similar in both directions. The relative convergence rates reach values of the order of 10^{-11} s^{-1} after a few years, comparable with the values measured for drifts with the same orientation.

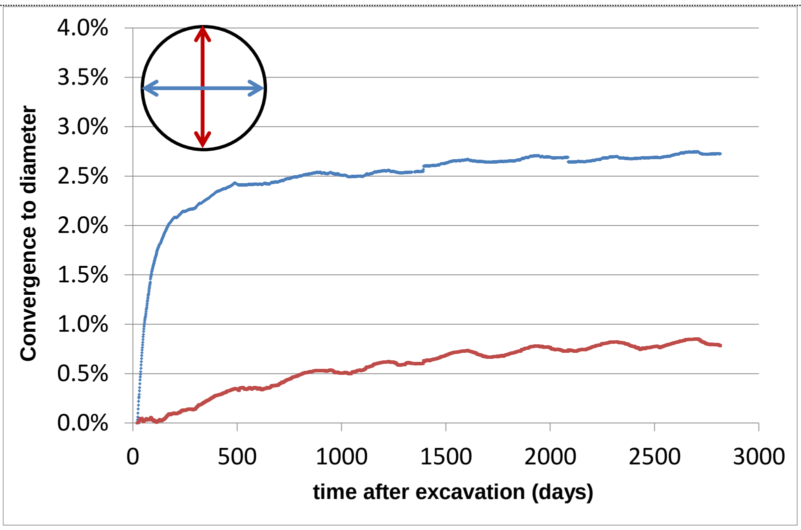

Figure 8 *Horizontal and vertical convergences of unsleeved cell ALC1603 at 16 m from the access drift*

PRINCIPAL LESSONS LEARNED

- ✓ The feasibility of excavation of a microtunnel 40 m long parallel with the major horizontal stress, with steel sleeve installation as excavation progresses, has been demonstrated, highlighting the following points:
  - The rate of progress of the excavation must be as continuous as possible at a sufficiently high speed to avoid any risk of blocking;
  - With the range of annular clearance obtained (20 mm), the casing must be installed as the excavation progresses;
  - Implementation of ‘flexible’ joints is recommended for the construction of sleeved cells;
  - Without sleeves, falling blocks are observed during the first 24 to 48 hours after excavation, suggesting non-circular geometry of the structure, then convergence of the rock wall is observed.
- ✓ The hydromechanical behaviour measured during excavation and over the longer term is similar in time course (but different in amplitude) to that measured for the larger-diameter drifts oriented in the same direction. Anisotropy of the HM response of the rock to excavation was observed, with regard to the time course of the pore pressure field and the damage around the cell and to the convergence of the walls.

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ANNEX 3

TPV Experiment

Experiment acronym / description	TPV	TBM excavation method and test of different kind of supports			
Type	☒ Scientific ☒ Technological	**Component(s)**	IL-LLW disposal section	**Sub-Component(s)**	Liner and support Damaged zone
Topic	Technological feasibility and hydro-mechanical behaviour				
Cigeo life phase	☒ Operation ☒ Post-closure 0 10^1 10^2 10^3 10^4 10^5 ans		**Level in the Callovo-Oxfordian**	☒ UA ☐ USC	

LOCATION

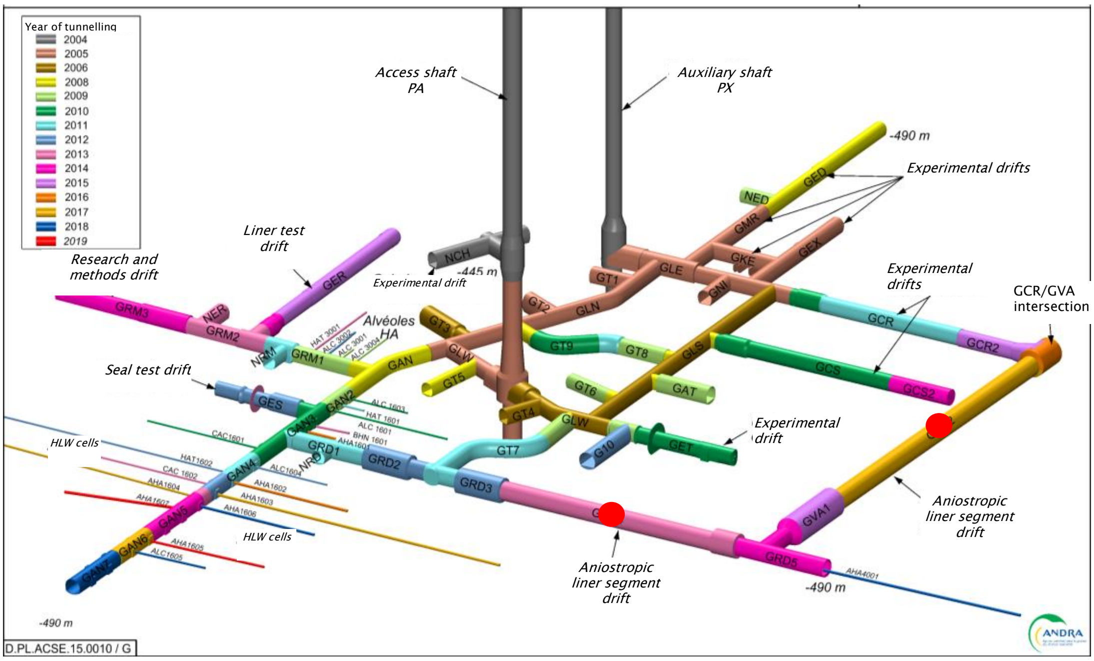


Figure 1 *Location of GRD4 and GVA2*

Drift GRD4 is oriented along the principal major stress (σ_H). Drift GVA2 is oriented along the principal minor stress (σ_h).

EXPERIMENT OBJECTIVE(S)

- **Demonstrate the feasibility of using a tunnel boring machine (TBM) for tunnelling and installation of precasted liner segments;**
- **Analyse the interaction between the rock and structure in the event of mechanised tunnelling using a TBM with installation of prefabricated liner segments;**
- **Study the mechanical behaviour of different "backfill/prefabricated liner" combinations, taking account of the mechanical characteristics of the materials used;**
- **Compare this tunnelling method and the effect of the time delay for liner installation with other tunnelling techniques used in the Laboratory and different types of primary and final supports used in other drifts.**

Start date: 2013	**Duration:**	**End date: Not defined (long-term monitoring)**

PRINCIPLE

The experiment involves tunnelling drifts with a partial face excavation machine and analysing the behaviour of the drifts. This test forms part of the technological and scientific characterisation test programme that focuses on analysing the hydromechanical behaviour of different underground structures at the Laboratory, performed with different excavation methods and/or support methods. This programme involves creating different parallel drifts with different construction methods and comparing the hydromechanical behaviour of the rock, in particular the characteristics and behaviour of the fractured zone and the variation over time of any strains/stresses in the support/liner. The first drifts were constructed using the conventional tunnelling method (CTM). Drifts GRD4 and GVA2 are drifts that are constructed using TBM (tunnel boring machine).

Four main variables were studied:

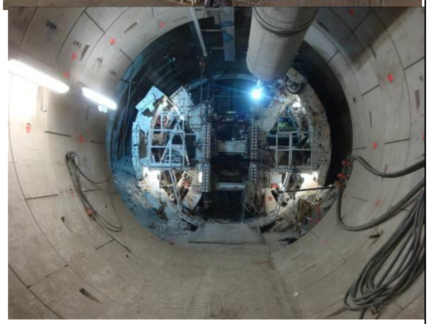
- Tunnelling direction;
- The use of two different types of backfill grout: “conventional” and “compressible”;
- The use of a (rigid) universal liner segment and the “VMC” segment (patented by Andra/CMC), which is a dual-layer compressible liner segment.

This behaviour was then compared to the behaviour of the other drifts (GCR, GER, GCS or BPE) tunnelled using a different method. Ongoing interaction between the TPV, ORS and OHZ experiments is necessary in order to properly describe the behaviour of the structure.

EXPERIMENTAL PROTOCOL and DESIGN

The concept for the experiment was based on operating feedback from previous tunnelling operations (SUG, OHZ and ORS experiments) with a view to an experimental strategy involving i) “mine-by-test”-type instrumentation installed in the rock prior to the test, ii) monitoring and instrumentation installed during tunnelling and iii) post-tunnelling monitoring, with a principal focus on characterising any induced fracturing and how it evolves over time. Sensors are installed in the packing mortar and on the liner segments in order to monitor strain and pressure.

Construction



- Herrenknecht partial face excavation machine, comprising a rotating excavator boom (850mm diameter), a metal shield (6.27m diameter / 4.0m length), a metal shield skin (6.23m diameter / 2.70m length and a backup train (9.70m length);
- Drift GRD4 tunnelled along σH: Excavation diameter 6.27m – length 89m – 93 rings of 0.8m comprising 9 liner segments (45cm thick) – two 30m test zones (conventional liner segments and conventional or compressible packing mortar) – packing material inserted using radial injection along a slop (keying at 18m from the working face) – excavated from June to December 2013;
- Drift GVA2 tunnelled along σh: Excavation diameter 6.27m – length 120m – 149 rings of 0.8m comprising 9 liner segments (45cm thick) – three 40m test zones (conventional liner segments and conventional or compressible packing mortar with shells) – excavated from May 2016 to December 2017;

Experiment design

- Monitoring of the rock’s hydromechanical response to tunnelling: “mine-by-test” instrumentation (OHZ);
- Monitoring of the liner’s mechanical behaviour (prefabricated segments) and the behaviour of the injected packing mortar, using displacement, strain and pressure sensors;
- Hydromechanical characterisation of the cement-based materials used;
- Characterisation of the fractured zone (samples at the working face and at boreholes (OHZ));
- Monitoring of variation in permeability over time (OHZ);
- Non-destructive testing of the final liner;
- A total of 762 and 1353 liner monitoring sensors were installed for drifts GRD4 and GVA2 respectively.

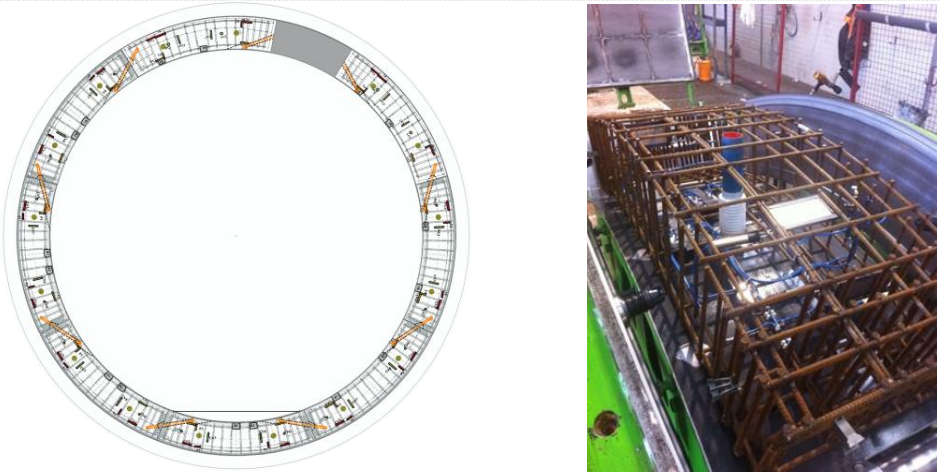


Figure 2 *Example of the instrumentation around one ring of liner segments (88 sensors): vibrating wire sensors and total pressure cells*

Instrumentation

The sensors in the liner segments on drifts GRD4 and GVA2 were inserted during prefabrication on the surface. The packing mortar monitoring sensors were fitted as the work progressed, and after the rings had been keyed. For each liner type, at least 2 sensor-monitored rings and 2 mortar monitoring sections were installed. A characterisation programme was carried out in the surface laboratory, with specimens of the concrete, injected mortar or compressible mortar produced when the liner segments were fabricated or the mortar was injected.

PARAMETER(S) MEASURED and NUMBER OF MEASUREMENTS ACQUIRED

Strain and pressure in the supports/liners.

PRINCIPAL RESULTS and LESSONS LEARNED

PRINCIPAL RESULTS

Liner installation and behaviour

- Liner installation (in particular VMC liner segments):
  - ✓ The feasibility of TBM excavation and segment installation was demonstrated.
  - ✓ The VMC liner segments were qualified, and their installation demonstrated (Figure 3).

Figure 3 *Prefabrication and installation of VMC liner segments in one of the 3 sections of GVA2*

- Analysis of liner behaviour
  - ✓ Variations in strain/stress in the liner segments was observed from the moment the packing material was injected, and these observations confirm the convergences reported in the rock. The stress on the ring of segments shows a double-sinusoidal pattern, which is the sign of an anisotropic load, showing prevalent horizontal convergence, which confirms observations from other drifts that were tunnelled in the same direction (Figure 4).

- ✓ The mechanical stress and strain signatures of the two zones that used different injection mortars (conventional and compressible packing material) show similar patterns. The values are higher in the zone where conventional packing mortar was used, which confirms that the use of a compressible packing mortar has a positive effect, reducing the force applied to the ring of liner segments.
- ✓ Analysis of the behaviour of GVA2 is still ongoing, awaiting the effects of loading becoming identifiable and interpretable (additional injection was completed in June 2018).

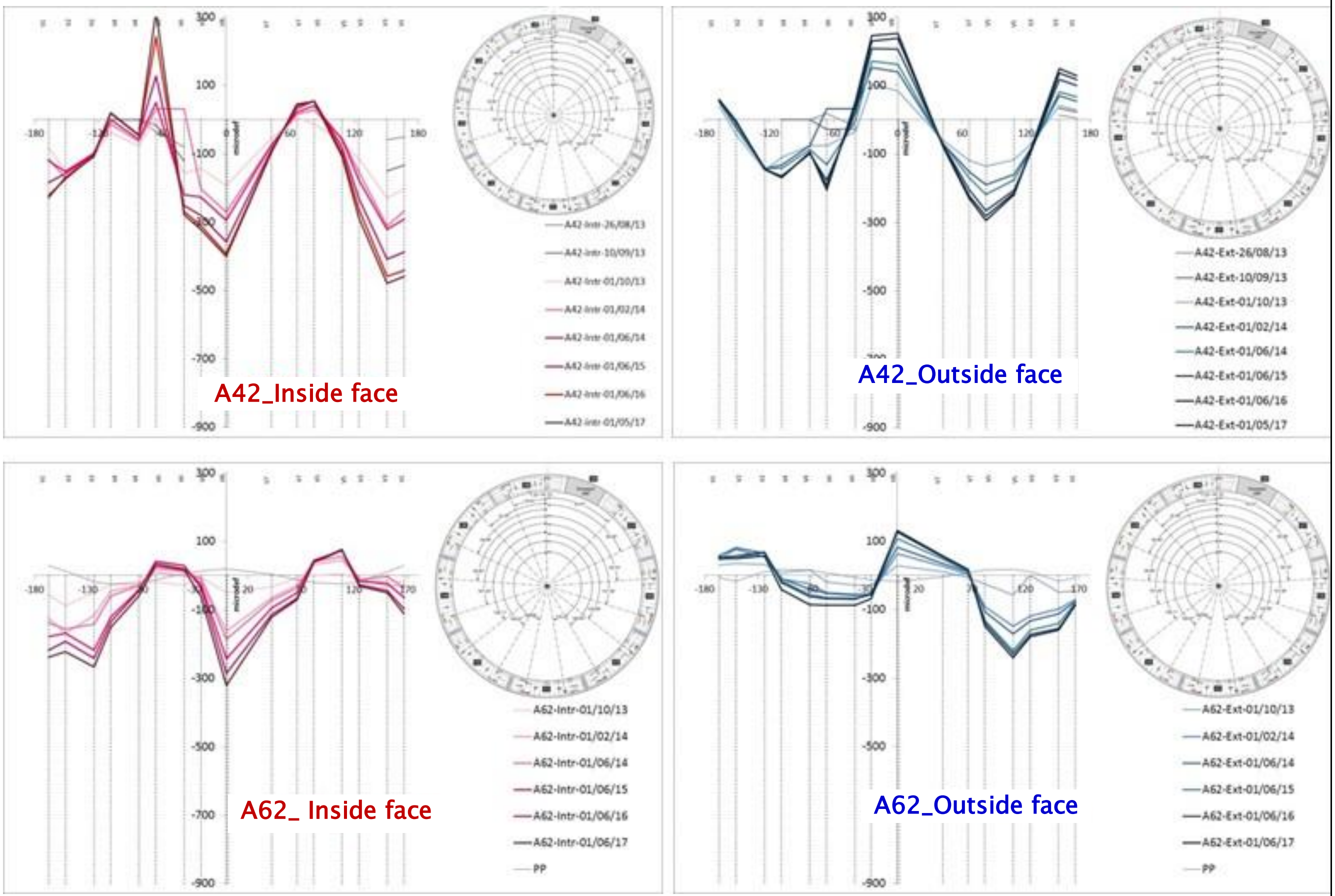


Figure 4 *Circumferential variation in orthoradial strain on the inside face (red) and outside face (blue) of two rings from GRD4. Ring A42 (conventional mortar injected) and A62 (compressible mortar injected)*

PRINCIPAL LESSONS LEARNED

- Excavation using a TBM was demonstrated at the Laboratory, with a good level of understanding of the hydromechanical behaviour of the structure and its liner;
- The insertion of compressible elements in the liner, either via the packing mortar or through the addition of a compressible layer in liner segment prefabrication, "limits and delays" loading in the liner.

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ANNEX 4

NSC EXPERIMENT

Experiment acronym / Name		NSC	Seal Core (*Noyau de SCellement*)		
Type	☒ Scientific ☒ Technological	**Component(s)**	Closure structures	**Sub-component(s)**	Clay core Retaining plug Damaged zone
Topic		Technological feasibility and hydromechanical behaviour			
Phase in the Cigeo facility's life		☐ Operation ☒ Post-closure 0 10^1 10^2 10^3 10^4 10^5 years		**Level in the Callovo-Oxfordian**	☒ UA ☐ USC

LOCATION

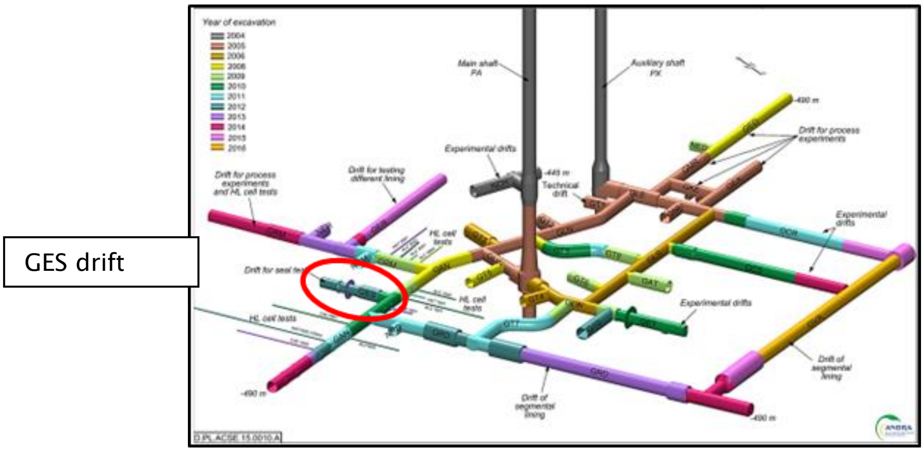


Figure 1 *Location of the NSC experiment*

EXPERIMENT OBJECTIVE(S)

- **Assess the overall hydraulic performance of a drift seal: this includes not only the seal itself but also the interface zone with the clay rock and the damaged zone in the vicinity of the seal.**

Start date: 2013	Duration: Long	End date:

PRINCIPLE

The principle of the NSC experiment is to mimic a seal at the scale of a Laboratory drift (5 m diameter) with a (swelling clay-based material) seal core between two concrete retaining plugs. The seal core is artificially hydrated using hydration membranes. Then, once saturation is achieved, an overall permeability test will be performed between upstream and downstream of the seal to estimate the equivalent (major) permeability of the seal. All flows in the core, at the core/clay rock interface and in the fractured zone will be estimated during test performance.

EXPERIMENTAL PROTOCOL and DESIGN

The seal core is 4.6 m in diameter and 5 m long. It is made of:

- ✓ Blocks (mix of 40% MX80 bentonite and 60% sand), representing ~95% of the filling material;
- ✓ Mix of (pure bentonite) powder and pellets, representing ~5% of the filling material;
- ✓ Dry density of swelling clay ~1.45 t/m^3, giving a swelling pressure at saturation of between 2.5 and 6.3 MPa;
- ✓ 319 sensors (99 for interstitial pressure; 76 for total pressure; 144 for humidity), 4 hydration membranes.

Two concrete retaining plugs (using low hydration heat concrete) retain the core:

- ✓ Injection chamber: 25 sensors (15 for strain, 10 for interstitial pressure) and 1 membrane (for core hydration then water injection during test performance = hydraulic upstream);
- ✓ Retaining plug: 88 sensors (36 for strain; 16 for displacement; 40 for interstitial pressure; 16 for accelerometry) and 1 membrane divided into sub-sectors (for core hydration and water collection during test performance = hydraulic downstream).

In addition, the NSC experiment includes:

- ✓ 1 radial groove around the circumference of the GES drift, enabling hydration of the connected fractured zone of the drift downstream of the retaining plug;
- ✓ 6 connecting boreholes for passing the sensors and lines for water injection into the seal core to the NRM niche;
- ✓ 19 boreholes for interstitial pressure measurement around the GES drift.
- ✓ 4 boreholes fitted with extensometers around the GES drift at the location of the core.

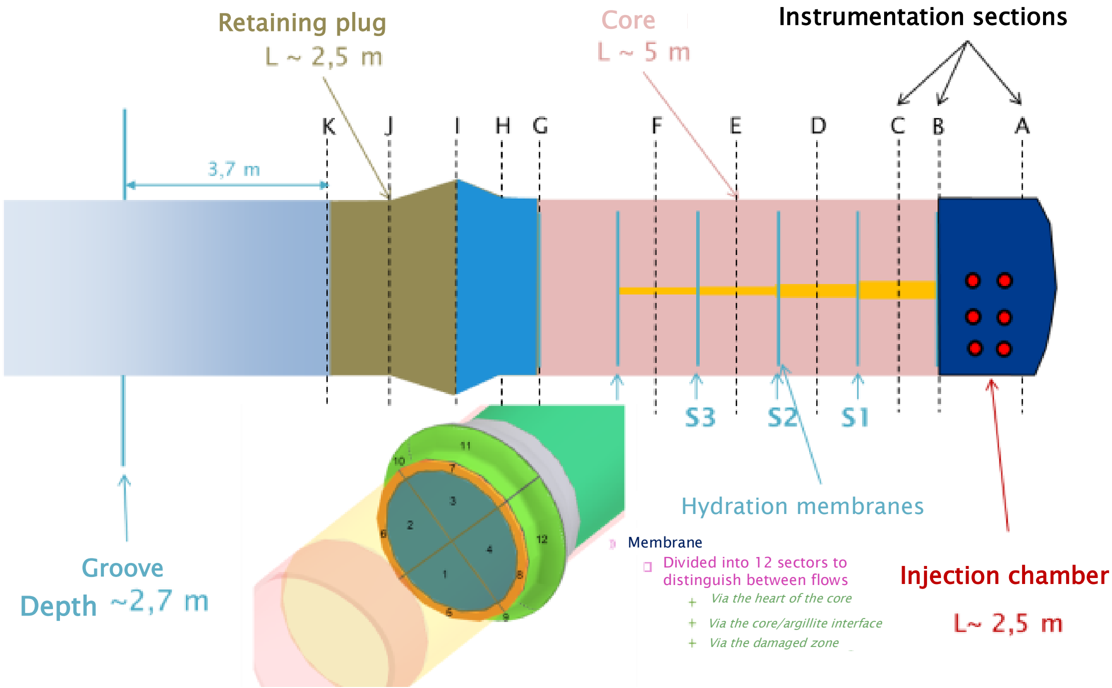


Figure 2 *Schematic cross-sectional view of the NSC experiment*

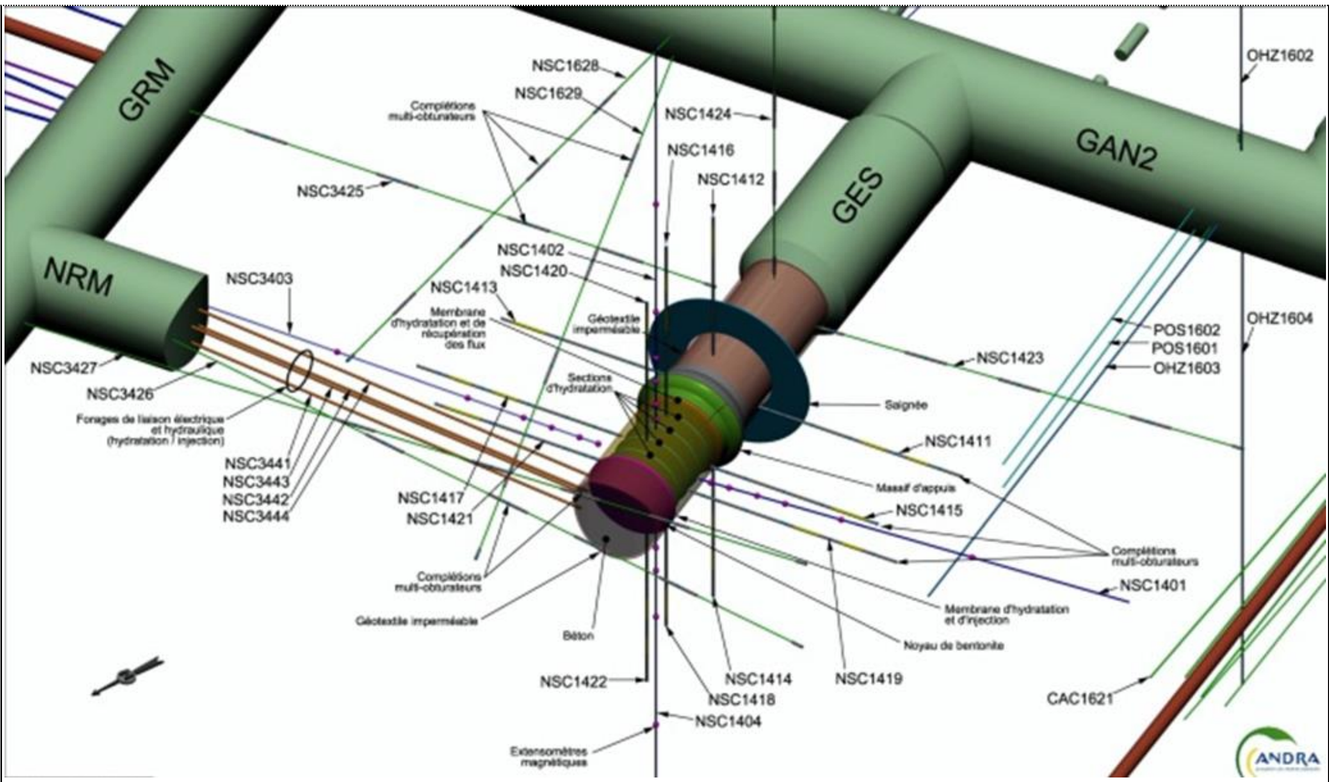
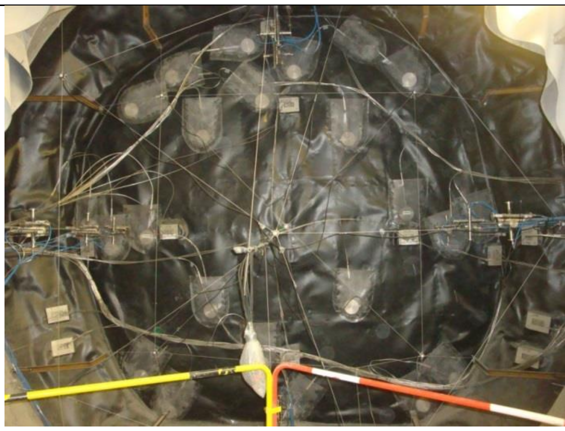


Figure 3 View of the external instrumentation of the GES drift

Seal core instrumentation before concrete casting in the injection chamber

Placement of blocks and installation of sensors in the core

Installation of membranes at the core/retaining plug interface (before concrete casting)



Installation of sensor instrumentation in the retaining plug (before concrete casting)

Figure 4 Photographs taken during the installation phase

Main steps of the NSC experiment:

- ✓ GES drift available end 2012;
- ✓ Installation of all seal instrumentation: January 2013 to March 2014:
  - Injection chamber: February to May 2013;
  - Seal core: June-July 2013 (6 weeks);
  - Retaining plug: August-September 2013;
  - Groove: November 2013 to March 2014;
- ✓ **Start of artificial seal hydration: 28 January 2014**

The geometry of the experiment, characteristics of the core and monitoring of the initial measurements are detailed in the reference document Andra (2015).

MEASURED PARAMETER(S) and NUMBER OF MEASUREMENTS ACQUIRED

In total, 420 sensors were installed along with 23 instrument boreholes, giving 866 measurement points.
In detail, there are :

- total pressure (76 measurements, in MPa),
- interstitial pressure (183 measurements, in bar, in the core, concrete and clay rock),
- relative humidity (144 measurements, in %RH, in the core),
- strain/displacement (130 measurements, in µm/m and mm, in the concrete and clay rock)
- ultrasonic monitoring of the downstream retaining plug (16 transmitters/receivers).

The volumes of water injected are measured via tanks placed on scales (21, in kg) associated with flowmeters (18, in ml/min).

From time to time, permeability measurements are made in the intervals of the boreholes around the GES drift.

Ultimately: Determination of the (major) equivalent permeability of the seal.

PRINCIPAL RESULTS and LESSONS LEARNED

Figure 5 shows the average total pressure and the average relative humidity of the seal core calculated from installation of the sensors until September 2018.

Mechanical equilibrium has not yet been reached. Complete saturation of the core has not yet been achieved after several years of water injection. In September 2018, the average relative humidity was between 97 and 98%. At that date, a water volume of 19.7 m^3 had been injected into the core. This volume is greater than the theoretical volume of the voids in the core, calculated for achieving saturation (~ 15.6 m^3). This difference is due to the fact that the water also hydrates the connected fractured zone of the GES drift and the pore volume of the shotcrete around the injection chamber. Furthermore, water continues to percolate intermittently around the downstream retaining plug. It is partly recovered at the groove in the drift slab.

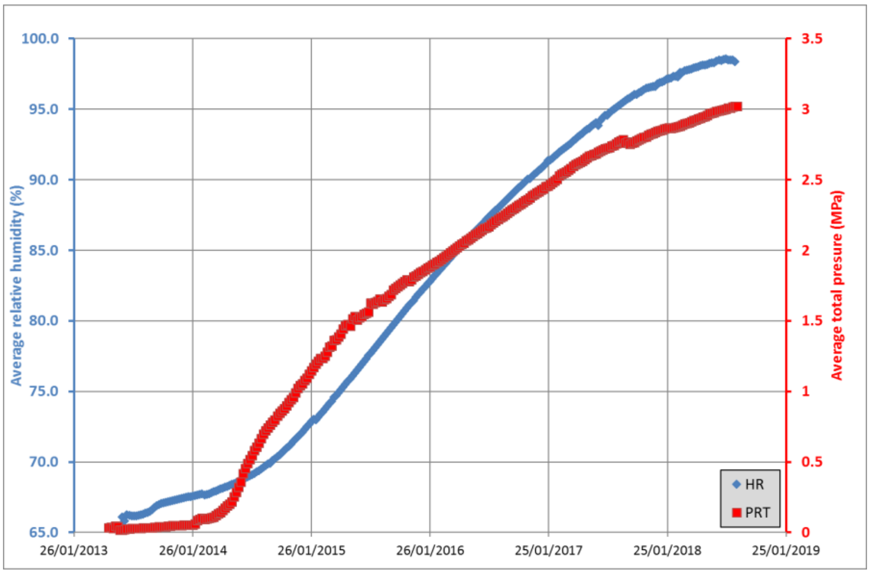
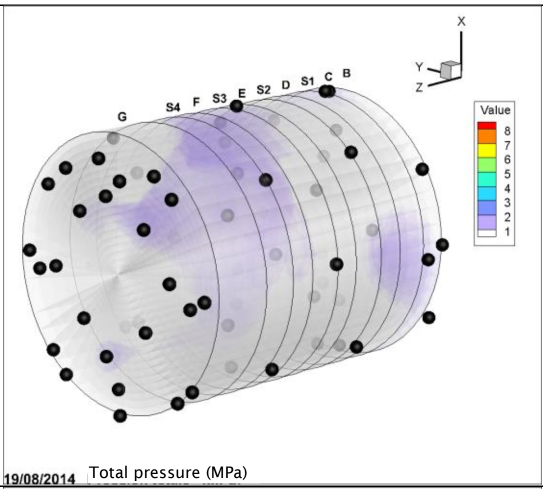
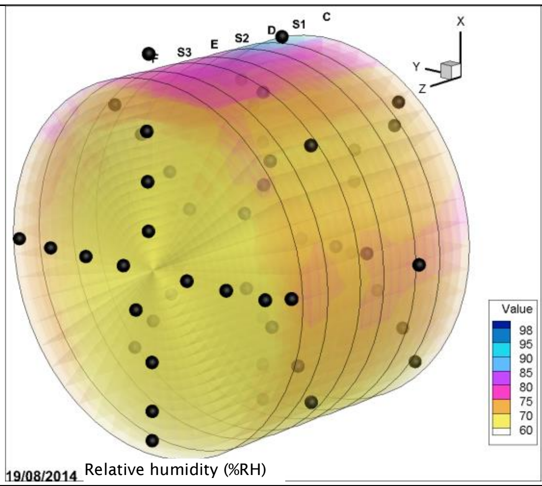
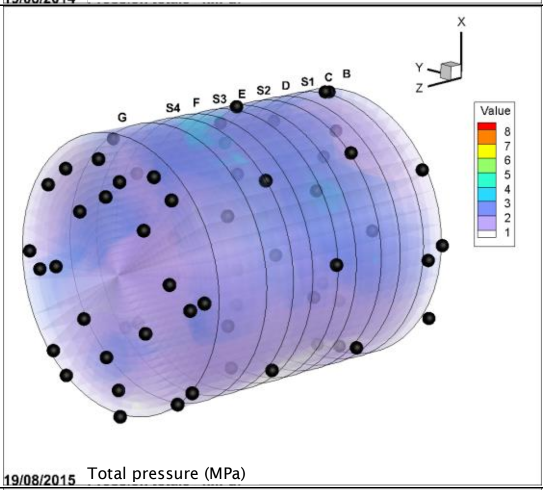
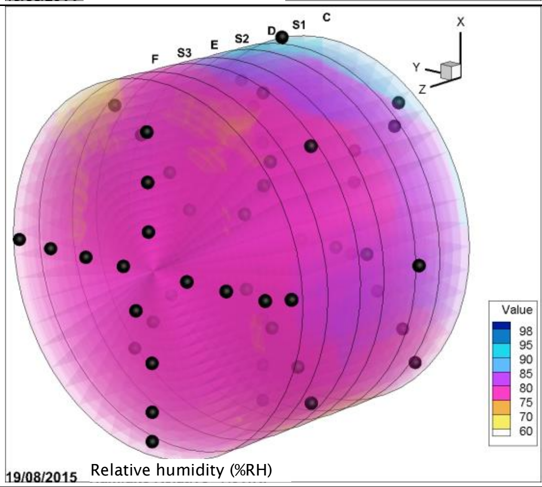
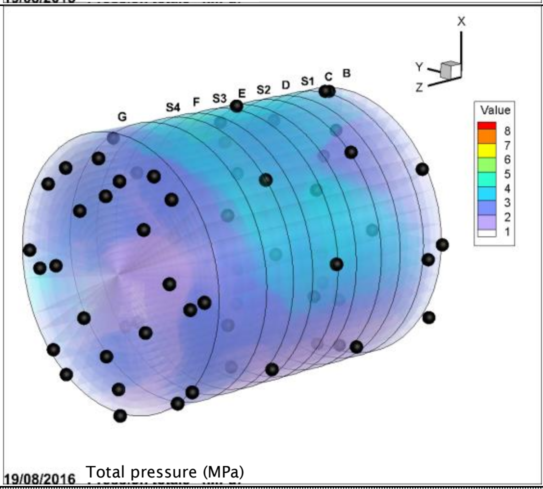
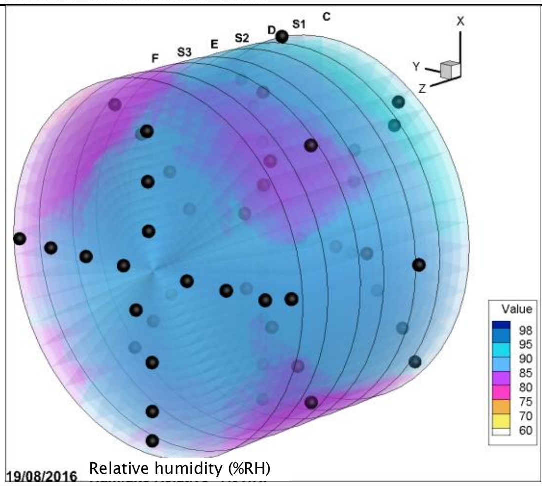
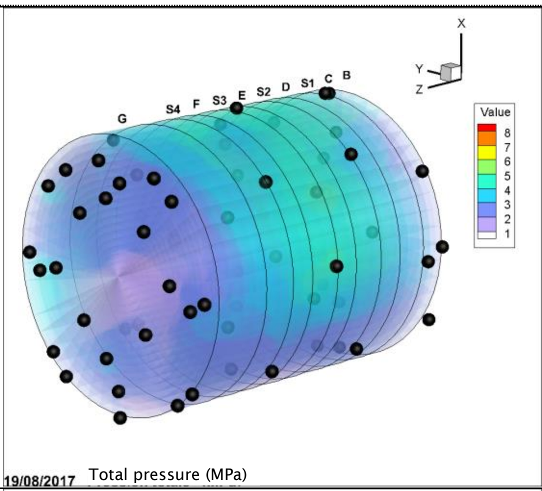


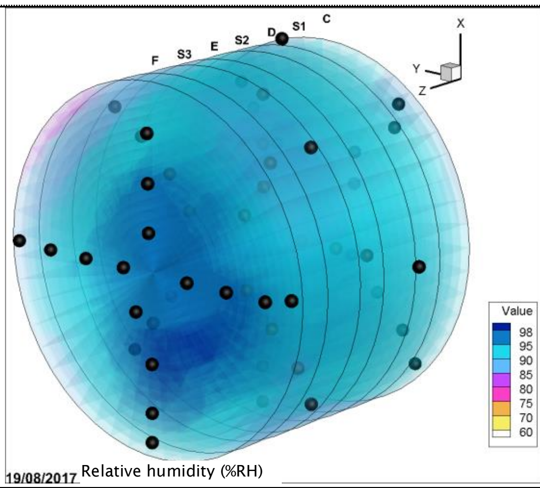
Figure 5 *Evolution of seal core average total pressure and average relative humidity*

Figure 6 gives a more detailed view of the total pressure and relative humidity measurements in the seal core during the saturation phase. During the hydration phase, preferential circulation is observed along the seal-clay rock interface and along some sensor lines. After 4.5 years of hydration, a certain non-uniformity persists in total pressures, but the relative humidity is gradually becoming uniform, with values between 89 and 100%.

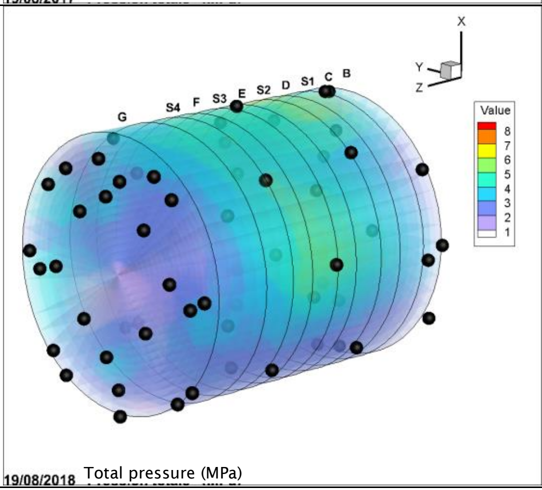
Δt since start of hydration	**Total pressure (MPa)**	**Relative humidity (%)**
6 months		
1.5 years		
2.5 years		

3.5 years





4.5 years



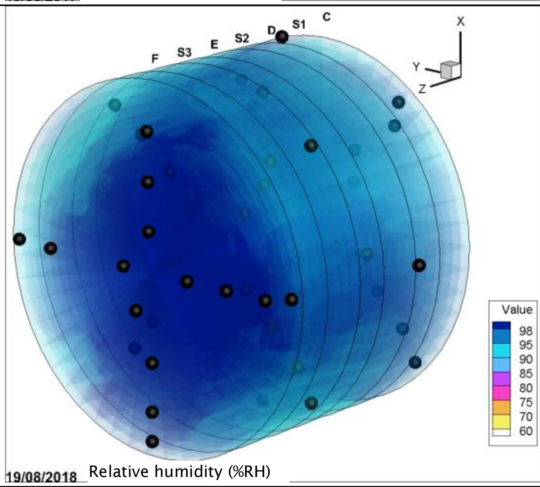


Figure 6 *3D view of the evolution of variations in total pressure (interpolation from 76 measurement points, left) and relative humidity (interpolation from 64 measurement points, right)*

REFERENCE DOCUMENTS

Andra (2015) *Expérimentation NSC – Bilan des mesures et suivi de la phase d'hydratation* (NSC experiment – Summary of measurement and monitoring of the hydration phase). Andra Document No. DRPAMFS150017.

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ANNEX 5

MVE Experiment

Experiment acronym / description	MVE	“Materials – Glass” – “Long-term” Test			
Context	The alteration of glass in disposal conditions involves three alteration regimes: initial rate, rate drop and residual rate (ref). A number of surface laboratory studies have been carried out, particularly at the CEA, to investigate these three rate regimes. Four series of experiments were launched to back up these tests at the Meuse/Haute-Marne Underground Research Laboratory in order to address the alteration regimes taking into account specific characteristics of the environment such as the site water chemistry. They are as follows: · MVE – “Long-Term” test (launched in October 2009), focusing on the residual rate glass alteration regime, · MVE – “Rate Drop” Test (launched in June 2010), described in this sheet, focusing on the glass “rate drop” alteration regime, · MCO “dormant tests” (launched in December 2010) which aim to study the long-term glass/iron and glass/clay rock interactions with various types of glass (multi-decade tests) · MAV (launched in June 2018) which brings together developments in the HLW cell concept with the introduction of a filling material in the annulus between the extrados of the sleeve and the rock.				
Type	☒ Scientific ☐ Technological	**Component(s)**	**HLW-LL disposal section**	**Sub-Component(s)**	**Vitrified waste** **Disposal container**
Topic	**Durability of materials/waste**				
Cigeo life phase	☐ Operation ☒ Post-closure 0 10^1 10^2 10^3 10^4 10^5 ans		**Level in the Callovo-Oxfordian**	☒ UA ☐ USC	

LOCATION

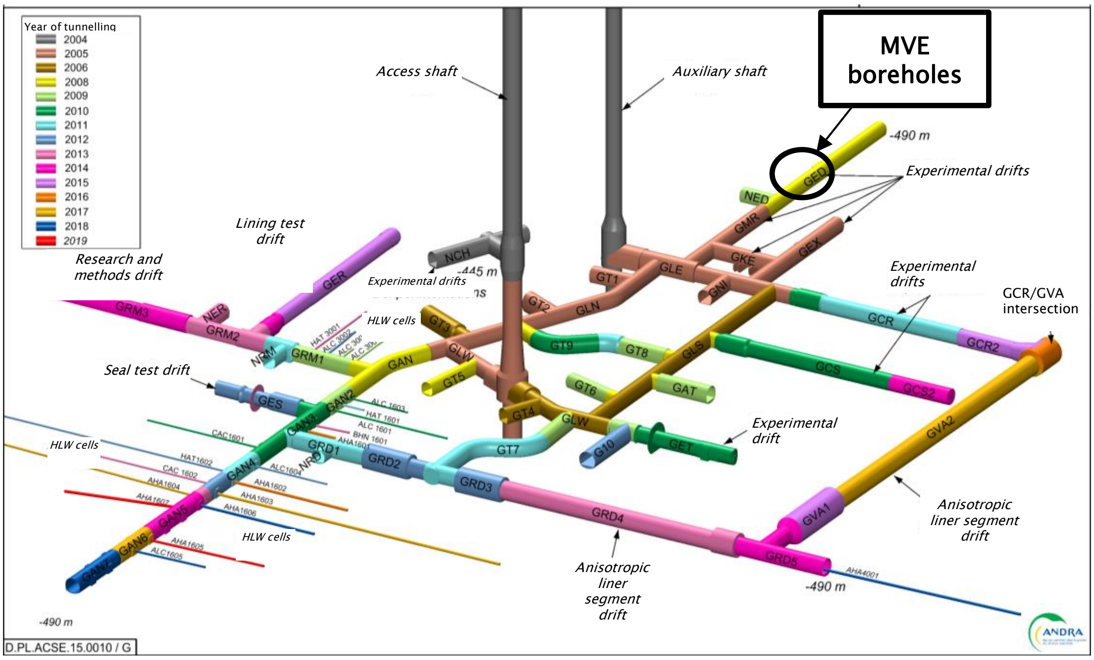

Figure 1 *Andra’s URL layout*

EXPERIMENT OBJECTIVE(S)

The “MVE – Long Term” test focuses on the alteration regime that occurs beyond the transient phase during which corrosion of the disposal container can influence the alteration kinetics of the glass (see MVE - “Rate drop” Test Experiment Record Sheet). In this “residual rate” regime, in standard conditions in pure water, the alteration rate is low, or even very low, but stable.

The objectives of the experiment were to:

- Assess the alteration rate of vitrified HLW with materials in the environment during the residual rate phase;
- Determine the nature of glass alteration products.

Start date: October 2009	**Duration:** Long-term	**End date:**

PRINCIPLE

The experiment involves a descending vertical borehole for testing *in situ* behaviour of glass powder in contact with the clay rock, in saturated conditions and at ambient temperature.

The glass powder used is SON68 glass, the inactive simulant for the R7/T7 glass used for vitrified waste packages at La Hague.

EXPERIMENTAL PROTOCOL and DESIGN

- **Equipment**
  - ✓ 1 350mm-diameter descending vertical borehole (MVE1202 borehole, Figure 2);
  - ✓ 1 completion (Figure 3 and Figure 4) fitted with:
    - 1 packer for isolating a test chamber of around 430mm in length;
    - 1 test chamber filled with a clay rock hollow cylinder (manufactured from a 290mm drill core). The internal hole (101mm diameter central hole) of this hollow cylinder comprised a stainless steel inner tube surrounded by a porous stainless steel filter then 2,078g of glass powder (150-250microm). The test chamber was initially saturated with water reproducing the composition of the Callovo-Oxfordian pore water doped with deuterium and iodine. Monitoring these elements can be used to assess diffusive transport around the borehole;
    - 1 network of hydraulic lines with 40 bars of pressure for setting up closed circulation of the aqueous solution between the interval and a module in the drift; the volume of water in the test interval is 22L and, there is 7L of water in circulation outside the interval;
  - ✓ 1 circulation module (pump, flowmeter, etc.), in-line analyses (redox potential, pH, electrical conductivity, temperature) and sampling (20 cells mounted in parallel within the water system).

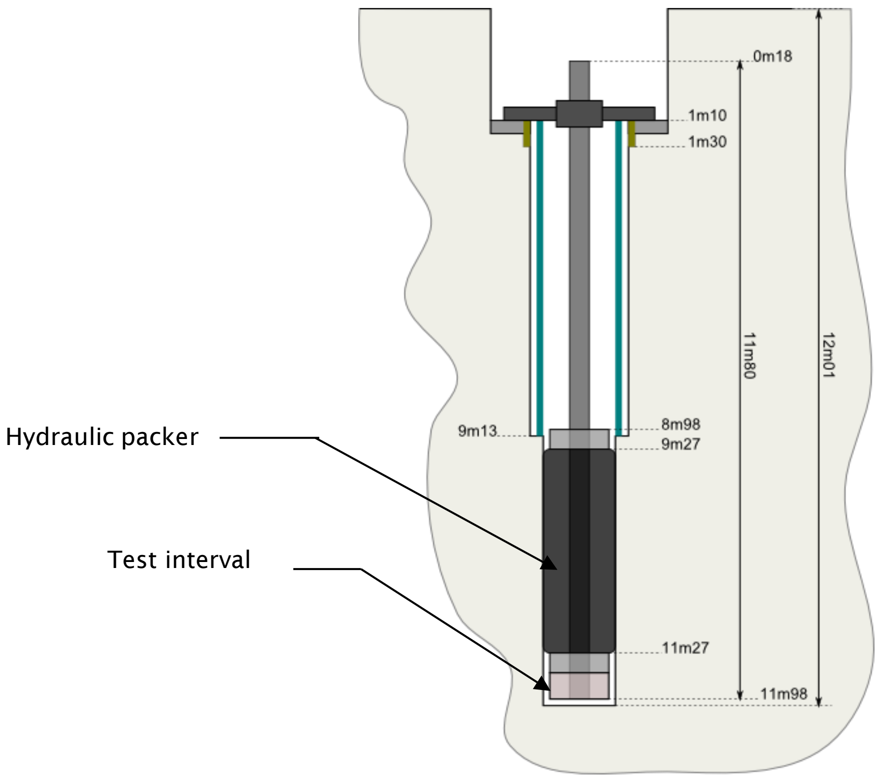

Figure 2 MVE1202 layout

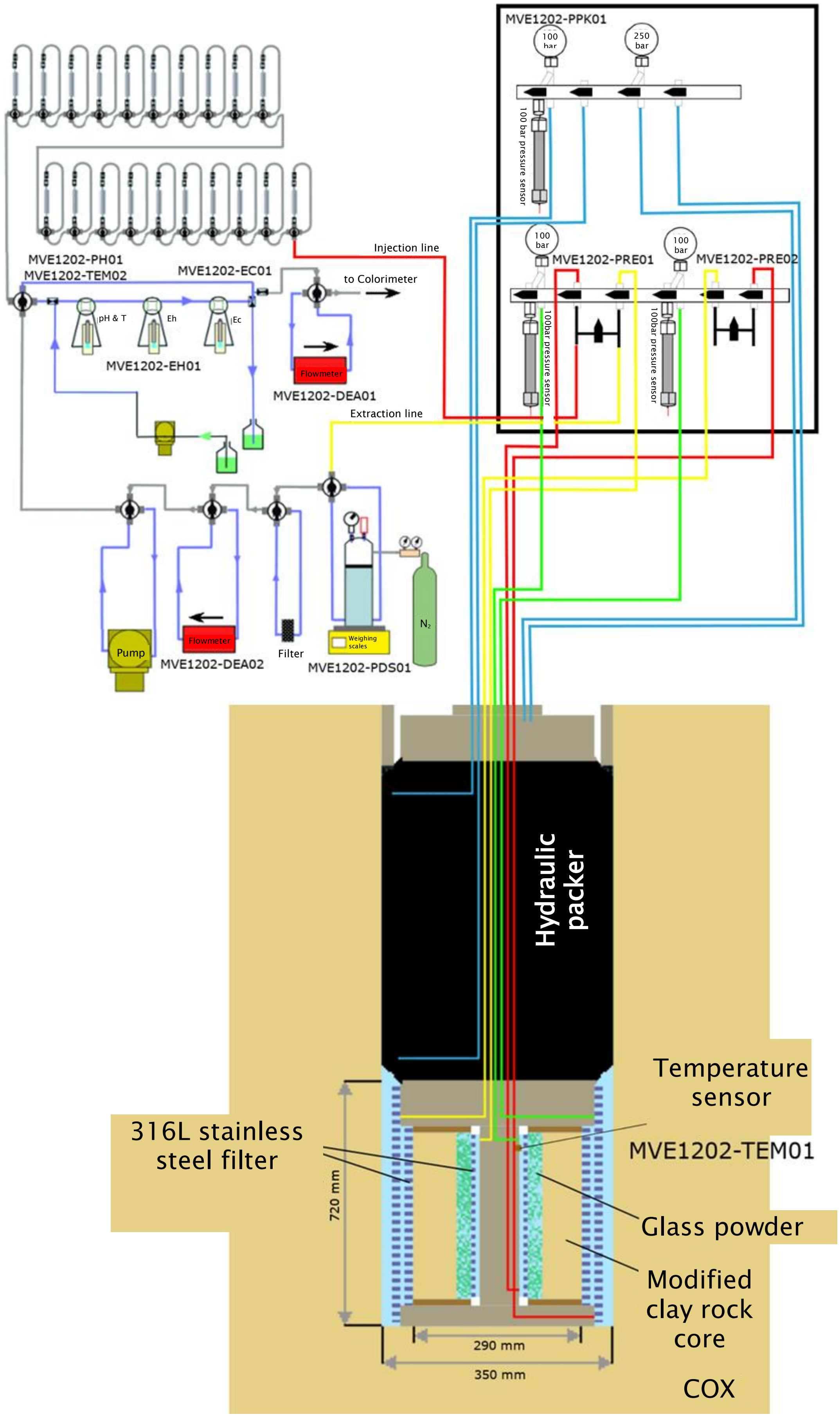

Figure 3 Diagram of the test chamber and associated hydraulic system

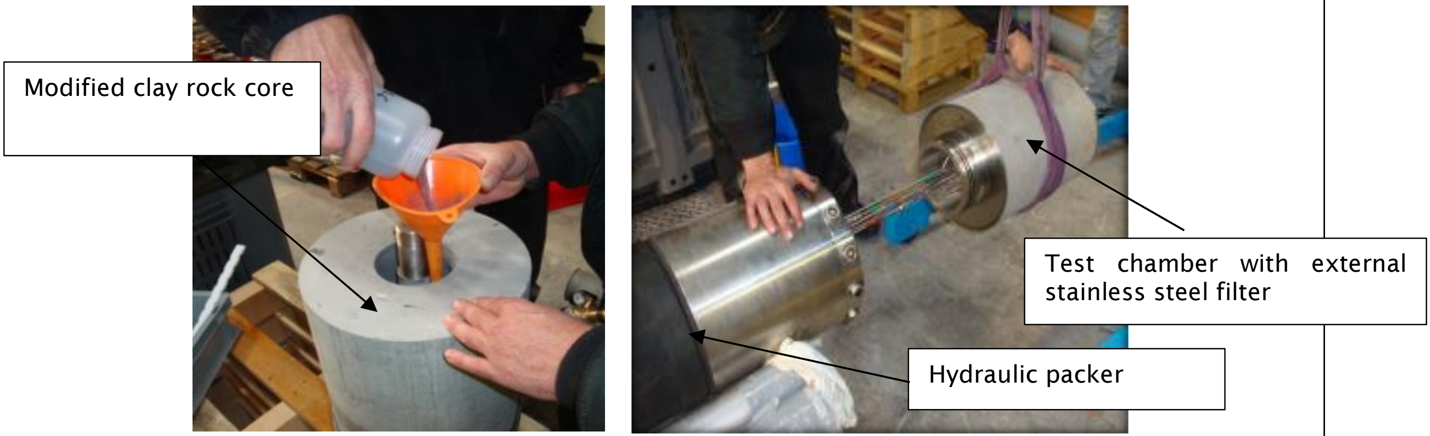

Figure 4 *Filling of the hollow cylinder ($Ø_{int}$ = 101mm) with glass powder and final assembly of the chamber*

Chemical composition of the SON68 glass

Table 1 *Analysed composition of the SON68 glass in element weight percent.*

Element	Si	Ca	Li	Zn	B	Cs	Al	K	Sr
El. wt.%	21.24	3.22	0.8067	1.977	5.35	1.063	2.56	0.4567	0.3433

Element	Ba	Na	Sn	Co	Cr	Ni	Fe	Mn	La
El. wt.%	0.615	7.823	0.0257	0.1833	0.0437	0.17	0.31	0.3567	1.753

Element	Nd	Ce	Pr	Zr	Mo	P
El. wt.%	2.093	4.15	0.5767	2.14	1.417	0.0823

Test steps

- Boring, installation: October 2009;
- Filling with water using the synthetic water simulating the chemical composition of the Callovo-Oxfordian (COx), doped with deuterium and iodine;
- Continuous monitoring of pressure, temperature and in-line sensors (redox potential, pH, electrical conductivity);
- Irregular occasional sampling of the solution (35 samples taken);
- The test is planned for completion in 2020-2021 after recovery of the test chamber.

PARAMETER(S) MEASURED and NUMBER OF MEASUREMENTS ACQUIRED

- Continuous pH, hydrotest, temperature and pressure monitoring.
- Concentrations of species in solution (Na, Ca, K, Mg, SO_4, Cl, Si, B, Li, Sr, Ba, Cs, Fe, Cr, Ni, D, I) 2 to 3 times a year
- Characterisation (MEB-EDS, MET, µ Raman and µ-DRX) of solid phases at the end of the test.

PRINCIPAL RESULTS and LESSONS LEARNED

PRINCIPAL RESULTS

- 9-year monitoring can be used to understand the alteration kinetics of SON68 glass in situ.
- The pH of the altering solution (
- *)* is close to neutral (6.6 – 7.8) for the first 9 years of the test performed at the temperature imposed by the location (22°C, over the first 200 days followed by a progressive rise under the influence of a thermal disruption caused by a nearby heating borehole, stabilising at 27 ± 1°C).

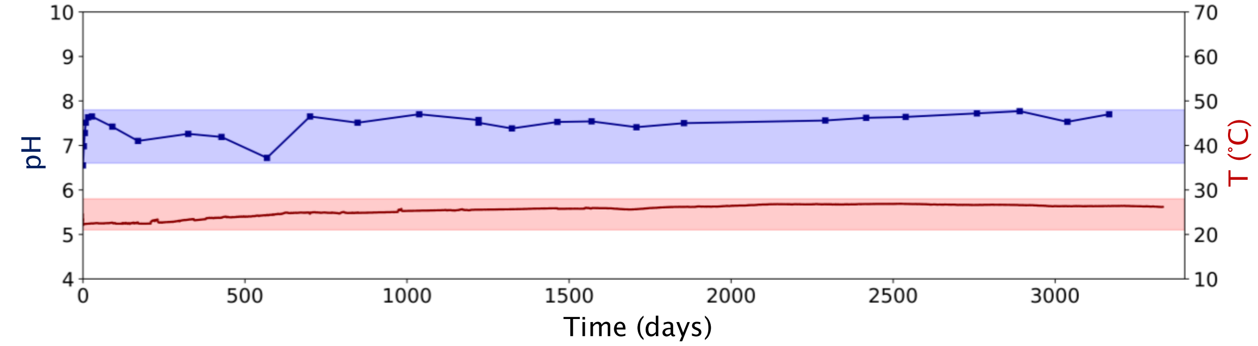

Figure 5 Variation over time of pH and temperature in the MVE1202 borehole test interval solution

- The redox potential is clearly negative (Eh ≈ -254mV SHE), reflecting anoxic conditions.
- The drop in sulphate concentration observed the first year could be a result of sulphate-reducing bacterial activity. The presence of bacteria with sulphate-reducing metabolism was confirmed using microbiological analyses. However, current results on alteration rates measured suggest that the bacterial activity detected does not have a significant direct influence on glass alteration kinetics.

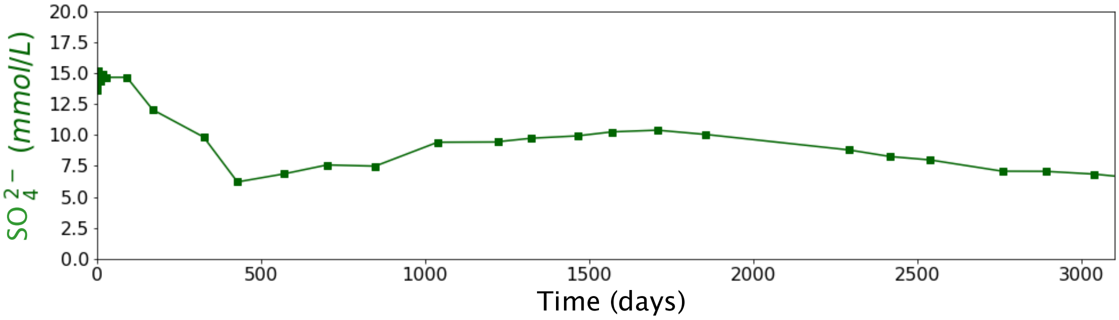

Figure 6 Variation over time of sulphate concentration in the MVE1202 borehole test interval solution

- Boron and lithium are tracers for glass alteration. As they are only present in trace amounts in the rock and the site water, variations in their concentrations reflect changes in the glass alteration reaction (Figure 7). However, the concentrations measured need to be corrected for losses due to diffusive transport in the geological formation. The diffusive transport characteristics will be obtained by modelling the diffusion profiles of the deuterium and iodine initially injected with the synthetic water. The alteration rate (v_i) can be estimated using concentrations in solution (C_i) by normalising with respect to the quantity present in the chemical composition of the glass (x_i) and the surface area of the glass (S) in contact with solution volume (V), $v_i = C_i.V/(x_i.S.t)$. However, in this test, the solution volume is not constant due to technical difficulties (leaks). The effects of dilution due to uncontrolled water inflows (from the geological medium due to a pressure gradient) also need to be taken into account to correct the concentrations measured from the analyses of the samples taken over the 9 years of test monitoring.
- The initial rate (v_0) is estimated at 6 x 10^{-3}g.m^{-2}.j^{-1}. Comparing this rate to those from surface laboratory tests shows that it is at least two times lower than the initial rate measured in synthetic clay water at 30°C and three times higher than the initial rate measured in pure water at 30°C (around 2 x 10^{-3}g.m^{-2}.j^{-1});

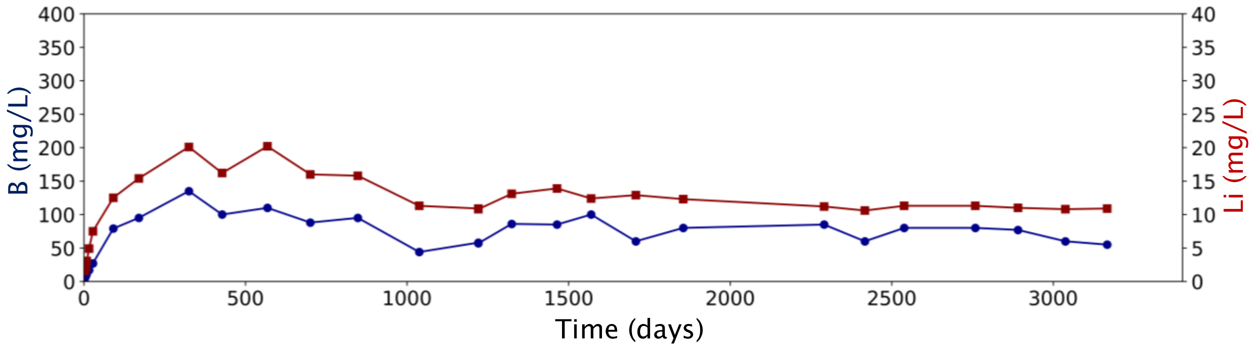

Figure 7 Variation over time of B and Li concentrations in the MVE1202 borehole test interval solution

- Boron and lithium concentrations in the solution show a strong drop in the alteration rate after a year. In the longer term, concentrations of dissolved silicon seem to approach a stable state, and the boron and lithium release rate drops again, probably reaching a value similar to the alteration rate observed in classic experiments in pure water (around $10^{-5}g.m^{-2}.j^{-1}$), but uncertainty and the fluctuations in measurements due to technical difficulties make it impossible to determine a precise residual alteration rate value. Furthermore, the MVE-Rate drop test (see MVE-Rate drop experiment record sheet) showed discrepancies between the rates determined based on analyses in solution and those determined based on thicknesses of altered glass, and precipitated borated phases, since boron is considered a glass alteration tracer. Interpretation of the analyses in solution should therefore be supplemented by characterisation of the altered glass after the test is stopped.
- The activities in progress up to disassembly of the test planned for 2020 (to sample the solid phase) will aim to keep the test as stable as possible in order to avoid disruptions and improve the quality of the long-term alteration regime estimate. Any retention of boron in the alteration layer will be observed during characterisation of the altered glass.

PRINCIPAL LESSONS LEARNED

- After nine years of testing, glass alteration rates observed are low, and the "residual rate" alteration regime has been reached. In order to obtain a series of usable measurements (with no technical problems) for quantifying the residual rate, increasing sample frequency is recommended (currently every 6 months).
- Final disassembly planned for 2020 will involve recovering the test chamber and backing up the rates calculated using concentrations in solution by estimating rates via the thicknesses of the alteration gels that will be observed.
- The last two years of testing will be used to fine-tune the estimate of the residual rate representative of the conditions and the configuration of this test: glass powder in altered in situ conditions in the Callovo-Oxfordian pore water with no iron or corrosion products.

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MVE – "Rate Drop" Test Experiment Record Sheet.

ANNEX 6

RES Experiment

Experiment acronym / description		RES	“Seismic monitoring network”		
Type	☒ Scientific ☐ Technological	**Component(s)**	Geological medium	**Sub-Component(s)**	
Topic		Geological medium / Instrumentation / Monitoring			
Cigeo life phase		☒ Operating ☐ Post-closure		**Level in the Callovo-Oxfordian**	☒ UA ☒ USC

LOCATION

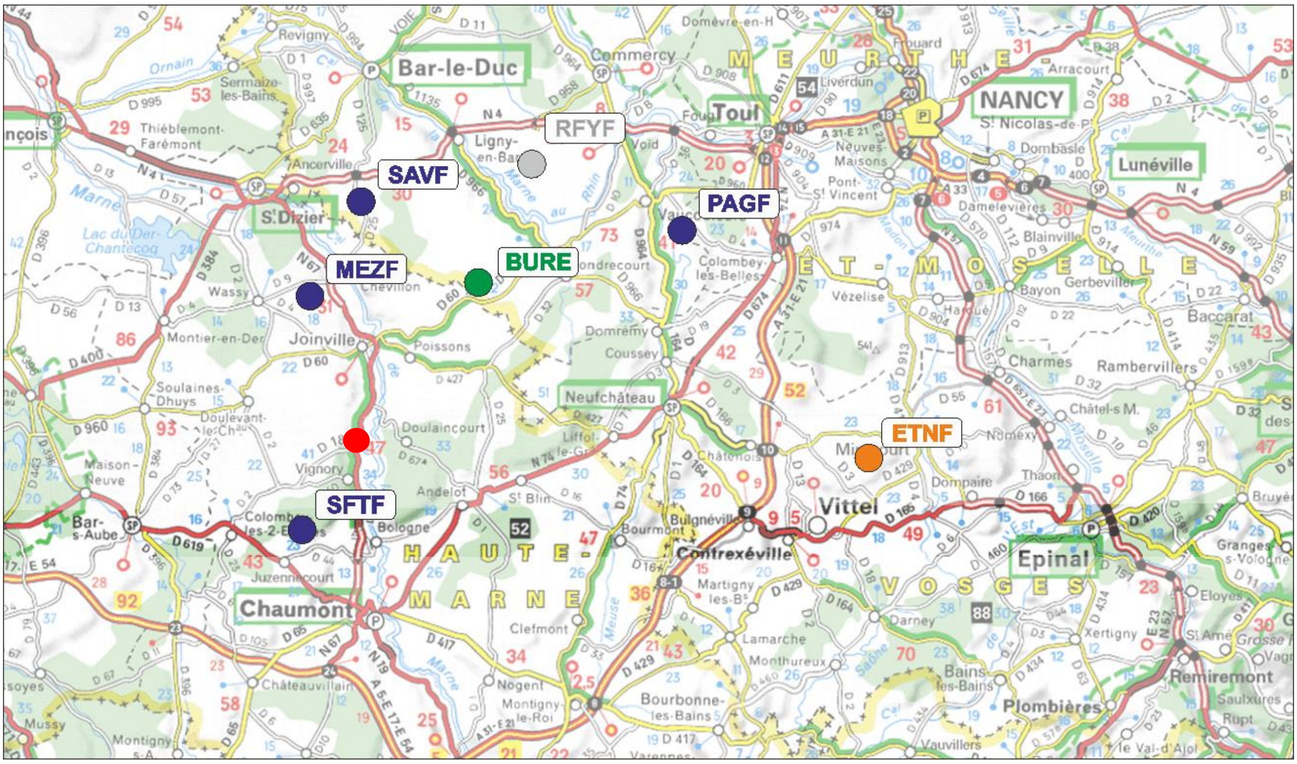

Figure 1 *Position of the 4 current seismic monitoring stations: PAGF, SFTF, MEZF and SAVF and the new ETNF station that became part of the network in late 2017*

EXPERIMENT OBJECTIVE(S)

The aim of the experiment is to set up a specific seismic monitoring network (French acronym RES) (*Figure 1*) in the region around the Underground Laboratory, in order to:

- observe the natural seismicity in the area immediately around the site (R = 20-30km) over the timescale of the monitoring period;
- analyse any activity from faults around the sector (either faults that are known on the surface or caped by the Mesozoic sedimentary cover).

In order to achieve these objectives, the measurement systems installed must:

- detect very low-magnitude events;
- sort between very low-magnitude events of natural origin and anthropogenic origin;
- accurately locate the epicentres of these events of different origins.

Start date: 2001	Duration: Long-term	End date: not defined

PRINCIPLE

As part of efforts to determine seismic movements to be taken into account for the safety of nuclear facilities, Andra commissioned the CEA/DASE/LDG to set up a specific seismic monitoring network (RES) in order to acquire precise sensor-generated data on the region in which the Underground Laboratory is located. In the so-called "Andra zone" centred on the Meuse/Haute-Marne site (Figure 2), the network currently comprises 4 Andra seismic monitoring stations and one LDG station (*Figure 1*). This network supplements the other national networks (the CEA/DASE/LDG digital seismic network (RSN), the National Seismic Monitoring Network (RéNass) and the French seismological & geodesic network (Résif)), which are used for regional and nationwide monitoring (Figure 2). The aim of the combination and interaction between these different networks is to generate precise data to characterise local seismicity (30km radius) and regional seismicity (80km radius) around the Meuse/Haute-Marne Laboratory. As far as possible, this system should also improve the monitoring of distant regional faults, such as the Metz and Vittel faults, which may relate to the seismicity of the "active" area in the Vosges.

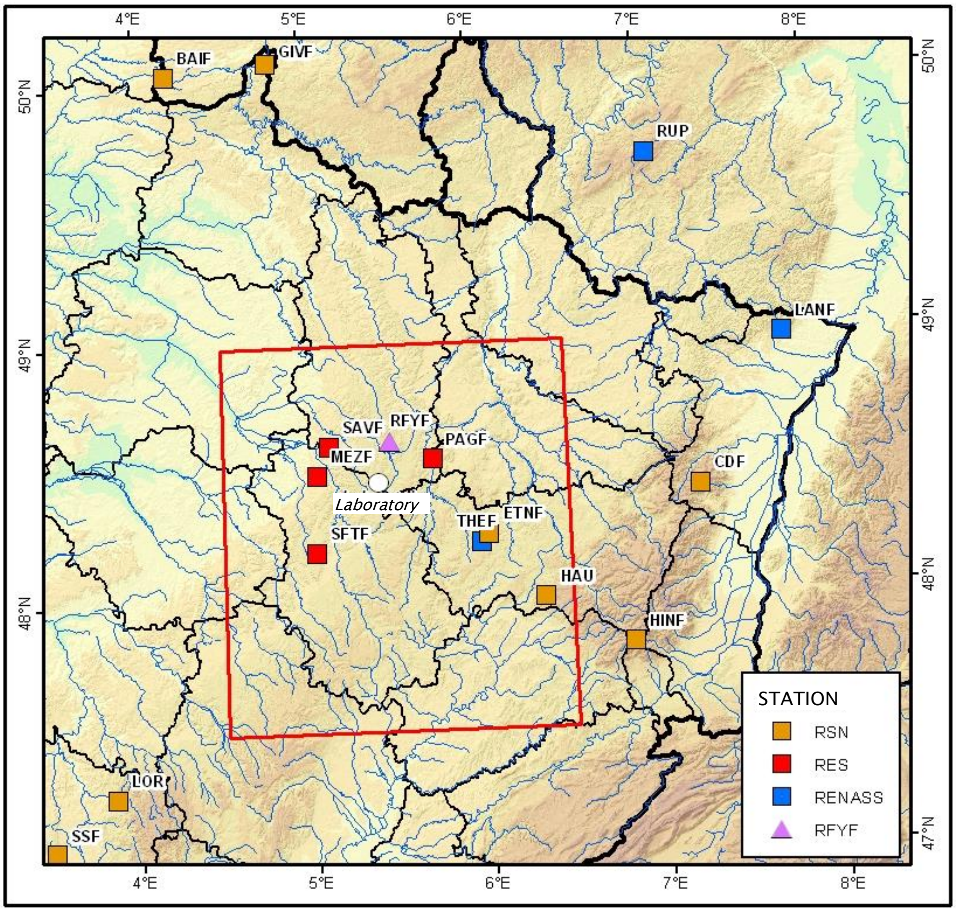

Figure 2 *Map of seismic monitoring stations used within the "Andra zone" (red rectangle) and across the wider region for seismic monitoring of the Bure site. It should be noted that the RFYF station (purple) has discontinued operation due to major interference from a nearby windfarm.*

EXPERIMENTAL PROTOCOL and DESIGN

- Geographical scope

Targeted seismic analysis focuses on the so-called "Andra zone" shown in red on Figure 2 defined geographically as follows:

- Northern boundary: 49°00'N to include the Toul faults, while avoiding interference and events caused by the seismicity from the former Sarre-Lorraine coal fields;
- Southern boundary: 47°30'N to include the area around the Vittel fault and seismicity further to the South;
- Western boundary: 4°30'E to incorporate the area around the Wassy fault with the area around the Marne faults;
- Eastern boundary: 6°30'E to include the Remiremont-Epinal seismic zone in the Vosges.

In practice, the area over which events are analysed is actually slightly extended by 0.05 degrees beyond the boundaries of the zone (i.e. 47.45°N-49.05°N and 4.45°E-6.55° E), in order take account of positioning inaccuracies. Future improvements in processing methods and better knowledge of the propagation model could allow certain earthquakes to be reintegrated into the study zone.

- Network description

The four seismic monitoring stations installed as part of the network each comprise one Mark Products L4 seismometer (3-component seismometer), a digitizer, an on-board PC and a satellite (Vsat, Figure 3) or GPRS telecommunications system. In 2017, an additional station (ETNF) was set up in the "Andra zone" and incorporated into the RES network (Figure 2), at the Estrennes (88) site, approximately 5 km from the former THEF site (previously provided by RéNaSS and now closed). It features a Trillium 120QA three-component broadband seismometer.

Limits on the detection capabilities of the four RES seismic monitoring stations are chiefly due to significant seismic noise from human activities (e.g. manufacturing, windfarms, roadways) and rather unfavourable geology (sedimentary rock), which is why no permanent monitoring station had been installed in the region prior to 2001.

Figure 3 *Components of a seismic monitoring station in the RES network (3-component seismometer, cable and IT cabinet with PC, digitizer, router, modems) and Vsat satellite dish*

Data acquisition is continuous at all stations on the different networks. The data logged is sent in real-time on working days to CEA/DASE/LDG via a satellite or GPRS connection for exploitation, processing and analysis.

- Integration with other networks

The overall objectives are achieved through the joint use of existing installations (RSN and RéNass networks shown on Figure 2), supplemented by the establishment and development of the RES network since 2001 (*Figure 1* and Figure 2).

PARAMETER(S) MEASURED and NUMBER OF MEASUREMENTS ACQUIRED

A seismic monitoring station continuously measures local movements caused by seismic waves affecting its location. Depending on the type of sensor used, the data recorded is close to the ground velocity or acceleration, via the sensor's transfer function. The main parameters measured in the data logged are the seismic wave arrival time, amplitude and dominant period. These systematic measurements over several years were used to determine Earth models (velocity, attenuation), which are still regularly being improved (tomography). The final parameter logged is the polarity of the seismic wave.

By combining the arrival times of the waves, as measured at various stations, the Earth models referred to above can be used to deduce the location (latitude, longitude and to a lesser extent depth) and origin time of the events. When the station is capable of logging the 3 components of ground motion, as it is the case for the RES network (either with a single sensor or 3 sensors oriented according to the 3 axes), the data can be combined to give the polarisation of the wave. Then the direction of travel and the angle of incidence from a body wave can be determined. This set of complementary parameters can be used in determining location.

Amplitude and dominant period are basically ways of determining magnitude, via attenuation models.

Finally, the polarity (positive or negative first pulse) has long been used for determining the earthquake focal mechanism .

Current trends focus on a more extensive use of the waveforms. Depending on the parameters extracted (from the spectral content to the full waveform including "all" seismic phases logged), inversion algorithms can be used to deduce more detailed characteristics of the seismic event (geometry, history, energy emitted and even depth). In order to promote reliability, these inversions require a large number of stations with a good geographical distribution, which is happening with the development of the Résif network, which Andra contributes to.

For example, 1090 events were logged and processed in 2017. These events can be broken down as follows (see Figure 4 and Figure 5):

- 16 earthquakes;
- 6 induced seismic events (presumed);
- 130 quarry blasts that have been located;
- 938 quarry blasts that have not been located;

The blasts that have not been located are quarry blasts in the Andra zone for which precise positioning is not required. Nonetheless, the quarry or group of quarries with which the event is associated is known.

PRINCIPAL RESULTS and LESSONS LEARNED

PRINCIPAL RESULTS

The 17 years of seismic monitoring in the area, and specifically in the "Andra zone" show that the work performed by CEA/LDG on targeted monitoring of regional seismicity meet the scientific quality criteria for seismology, meeting objectives in terms of monitoring, improvement of detectability, precision in horizontal location finding and in zone discrimination. This work has confirmed the aseismic nature of the Andra zone, in comparison with the Vosges area and the "*seuil de Bourgogne*" (Burgundy sill) (see Figure 4).

Through targeted monitoring using the RES network, combined with a revision of the seismicity in the zone and a temporary experiment in the North-East of the zone, most quarry blasts could be characterised, showing that a very high proportion of the records were actually such blasts (Figure 5); reliable characterisation is now possible using objective discrimination criteria. This has enabled Andra to agree to an easing of the systematic monitoring of activity at most quarries in the area. Finally, the potential benefit of developing a regional propagation model appears limited given the low density of stations in a 100km radius around the Bure site.

It has been shown that the natural seismicity logged with geographical locations between 1962 and 2017 as shown in Figure 4remains low to moderate, with no notable seismic events other than the events in the Remiremont, Epinal and Saint-Dié sector, and events related to seismic activity in the mines of North-Eastern France (Sarre-Lorraine coalfield). This activity was chiefly located on the edge of the Paris Basin to the East of a line running through Toul and Langres.

No significant earthquake occurred since 2001 within the "Andra zone" to the West of a line running through Langres-Neufchâteau-Toul, in other words close to the Bure Laboratory (i.e. less than 30km) and in the direction of the Paris Basin.

However a very minor earthquake of magnitude ML=0.9 close to Vitry-le-François occurred in January 2004 and three induced seismic events related to the gas storage site at Trois-Fontaines-l'Abbaye near Saint-Dizier (55) were monitored in 2017.

The closest event to the Laboratory, of magnitude ML=1.7, occurred on 16/11/2008 at 02:24, 13km to the North-East of Neufchâteau and approximately 30km to the East of the Meuse/Haute-Marne Laboratory site.

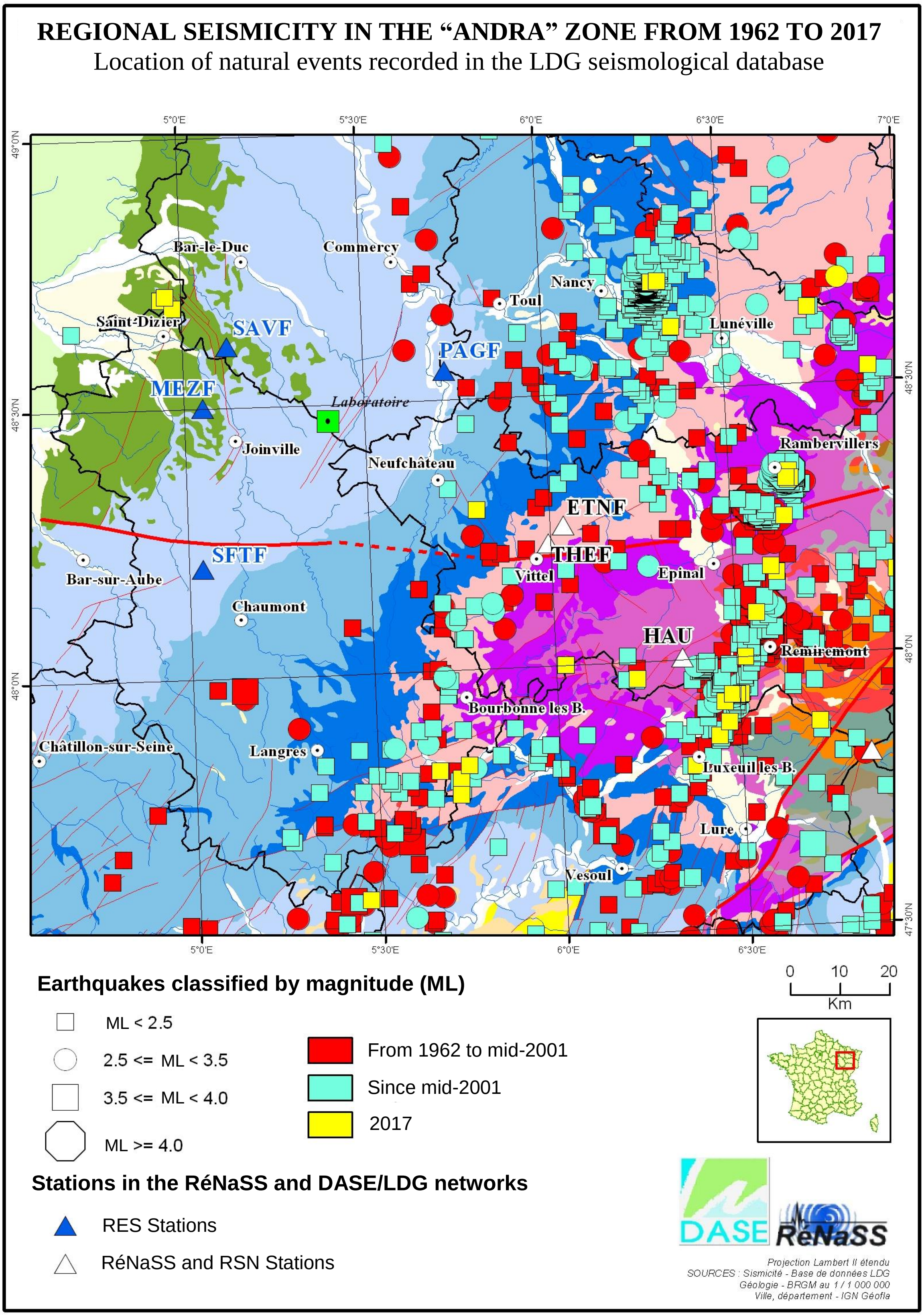

Figure 4 *Map of natural seismicity (standard model) in the "Andra zone" over the period 1962-2017 overlaid on a geological map*

REGIONAL SEISMICITY IN THE “ANDRA” ZONE FROM 1962 TO 2017

LDG locations incorporating LDG and RéNaSS data

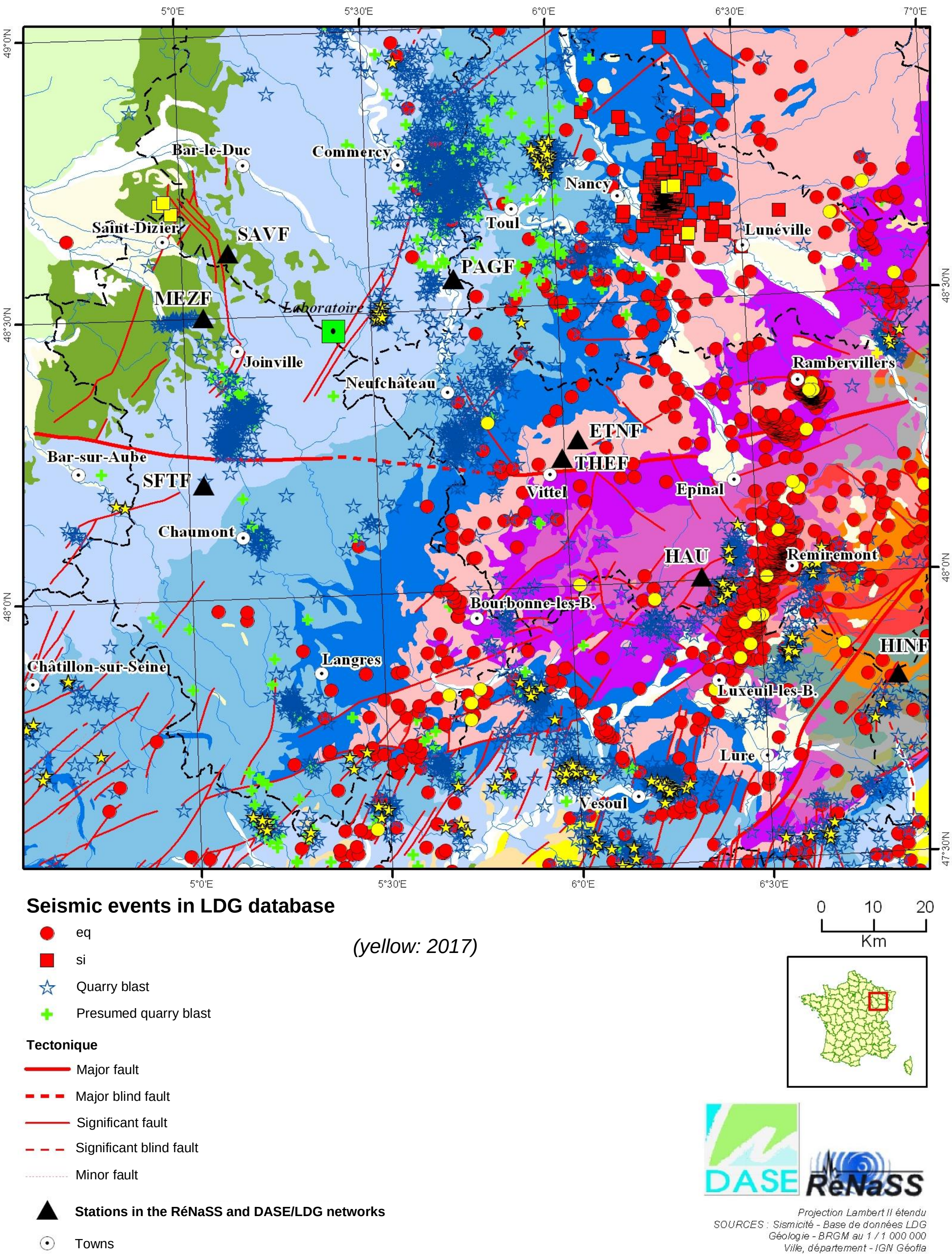

Figure 5 *Map of all seismic events (natural, induced and quarry blasts) from 1962 to 2017*

PRINCIPAL LESSONS LEARNED

The main conclusions set forth in Mazet-Roux and Cansi (2017) can be summarised as follows:

- the 2003 review of regional seismicity based on events logged by the CEA/DASE national monitoring network and RéNaSS has generated an updated background seismicity for the region, which is consistent and common to the two bodies;
- the low magnitude of events located in the study zone has led to biases in locations, in particular uncertainty about the depth of earthquakes;
- a few earthquakes, generally of a magnitude less than 3.5, located close to tectonic faults whose quaternary activity has not been demonstrated are not sufficient to qualify a fault as active. Conversely, the low level of activity recorded over the last five decades of observations (and last few centuries for historical events) does not mean that these faults are inactive. All we can say is that the 56 years of instrument-based observations do not highlight any active fault in the 50km sector around the Bure site;
- targeted monitoring in the “Andra Zone” with systematic acquisition of all signals from the detected events, whatever their origin, has highlighted significant activity in local quarries (Figure 5), which means that events in the best-known quarries now no longer need to be processed. Discrimination criteria are now routinely used, but some of them have also been reinjected into past seismicity, giving a very different picture of the natural seismicity in the area; this is now observed to be almost exclusively concentrated in the East (towards the Vosges) and South (near the “*seuil de Bourgogne*” / Burgundy sill) (Figure 4 and Figure 5).
- finally, with respect to induced seismicity, three induced seismic events have, for the first time since the start of the RES network, been logged close to Saint-Dizier (55) (Figure 5). These events would not have been detected were it not for the Andra SAVF station approximately 15km away. Unlike the induced tremors near Nancy, which were imputed to the Cerville underground natural gas storage site, these three events can be imputed to the Trois Fontaines-l’Abbaye storage site. The site has been “mothballed” (i.e. reduced operation) since 2012, which explains why the number of induced seismic events is low compared to the Cerville site. However, the three events in question occurred in the middle of the night and in mid-winter, which is exactly the periods when gas is extracted.

No.	CRITERION	DESCRIPTION	CHARACTERISATION	
			EARTHQUAKE	BLAST
1	Origin time	/	Variable	Working days and hours
2	Epicentre location	/	Known tectonic features	Quarries
3	Magnitude	Local magnitude (ML) or duration magnitude (Md)	Variable	Between 1.5 and 2.9 (very few with magnitude ML > 3)
4	Focal depth	/	Variable	Shallow
5	Wave polarity P	/	Variable	First amplitude of wave P positive at all stations
6	Ratio P/S	$PdivS = \frac{Ep}{Es}$	Variable	Between 0.4 and 1.2
7	Surface wave	LF wave (1 Hz) in the S wave coda	Variable (in general: NO)	YES
8	S wave spectrum	Frequency content of S wave	Broadband ([2 ;16])Hz	Low Frequency ([2 ;6]Hz)
9	S wave spectral ratio	$RapSpec = \frac{\int_{10}^{14} fft(S) \cdot df}{\int_{2}^{6} fft(S) \cdot df}$	Greater than 0.75	Less than 0.75
10	Recurrence	Repeated similar signal	Seismic crisis (main tremor + aftershocks)	Cluster of blasts (events of similar magnitude)
11	Confirmation	/	SIRENE database	By the quarry operator

Figure 6 Discrimination criteria for distinguishing earthquakes from blasts developed for and used by Andra

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