LUCOEX

(Contract Number: 269905)

DELIVERABLE (D-N°:3.2)

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Reporting period: 01/01/11 – 30/06/12

Date of issue of this report : 25/11/11

Start date of project : 01/01/11 Duration : 48 Months

Project co-funded by the European Commission under the Seventh Euratom Framework Programme for Nuclear Research &Training Activities (2007-2011)		
Dissemination Level		
PU	Public	x
RE	Restricted to a group specified by the partners of the [Lucoex] project	
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[Lucoex]

WP3 - ALC FULL SCALE EMPLACEMENT EXPERIMENT

TEST PLAN

CONTENTS

INTRODUCTION

1. Background

Under the terms of French Act 91-1381 of 30 December 1991, the *Agence Nationale pour la gestion des Déchets Radioactifs* (ANDRA, the French National Agency for the Management of Radioactive Waste) has built the *Laboratoire De Recherche Souterrain De Meuse / Haute-Marne* (LS, the Meuse / Haute-Marne underground research laboratory) in Bure (in Meuse – Haute-Marne *départements*), where science and technology experiments are performed.

From 28 June 2006, French Planning Act 2006-739, pertaining to the sustainable management of radioactive materials and waste, extends the scope of the 1991 "Bataille" Act by specifying that it is planned, by 2015, to assemble all the elements required for an authorisation for reversible disposal in a deep geological repository. The commissioning date for a possible repository has been set for 2025, which is compatible with the expected production of high-level and long-lived radioactive waste by the French nuclear cycle.

The underground laboratory consists of:

- a 5 m final-diameter access shaft and a 4 m final-diameter auxiliary shaft, which are 500 m deep and 100 m apart,
- a T-shaped horizontal experiment niche with a cross-sectional area of approximately 17 m² and 25 m of useful length, located at the -445 m level from the access shaft,
- a network of drifts accessible from the -490 m level, comprising connection drifts approximately 600 m long, which has experimental drifts attached; other planned test and exploration drifts are to be produced later.

The general layout of the laboratory drifts is shown in Figure 1.

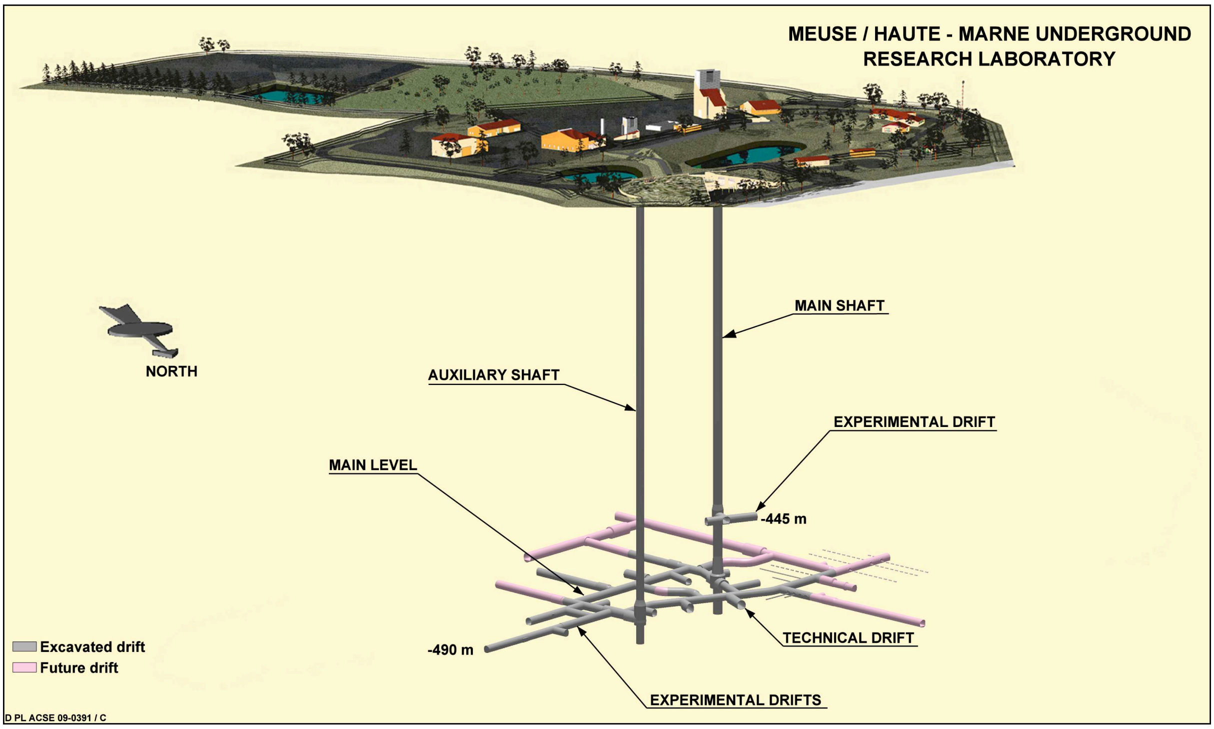

Figure 1 Laboratory layout.

The whole sedimentary series subject to this research dates from the Jurassic period. It is a predominantly limestone series comprised of monocline argillo-marlaceous (Kimmeridgian and Callovo-Oxfordian) layers of very low permeability, with a 1° to 1.5° dip to the north-west. There are some regional low-amplitude undulations.

The main purpose of the Andra research is to understand the Callovo-Oxfordian argillite formation, which is found below the -422 m level of the access shaft. The underground laboratory drifts are dug in this formation at the -490 m level.

The laboratory is a research facility located in the Callovo-Oxfordian argillite layer to be studied. The research performed in the underground facilities has the following aims:

- check the constructability of a possible repository in the Callovo-Oxfordian formation, and its reversibility options,
- confirm that the disturbances created by a possible repository in this formation are of limited range,
- confirm the containment properties of this formation,
- check its geological uniformity,
- check the ability to seal the works.

This research is comprised of:

- geological observations and measurements made as the underground facility excavations progress,
- taking geological samples,
- experiments in boreholes, shafts and sections of drifts,
- tests to check that excavation and cavity-support procedures are compatible with reversible disposal,
- possible tests of the installation and removal of dummy packages and back-fill materials.

The experiments that are the subject of this document are those which are to be implemented for Phase 3.1 of the “HLW cell” Programme Unit. Phase 3.1 is to be performed in the GAN drift.

2. Purpose of the document

This document comprises the specifications for measurements and instrumentation for Phase 3.1 of the "HLW cell" Programme Unit. It describes the HLW cell concept, gives experience feedback from Phases 1 and 1b of the “HLW cell” Programme Unit, outlines the aims of Phase 2, implemented from June 2011, and specifies the aims and experimental concept of Phase 3.1.

3. Document structure

Apart from the introduction, the document is in two parts:

- Part 1 describes the aims and experimental concept of Phase 3.1 of the “HLW cell” Programme Unit.
- Part II concerns the risk analysis.

PART I – AIMS AND EXPERIMENTAL CONCEPT

1. Summary of the "HLW cell" demonstration programme

1.1 "HLW cell" concept

In the benchmark concept, the HLW cell (Figure 2) is a microtunnel approximately 40 m long and 0.7 m in diameter. It comprises a "useful part", approximately 30 m long, for package disposal and a 10-metre-long cell head. They are to be favourably aligned with respect to the field of natural mechanical stresses. The useful part of the disposal cell, where the packages are placed, has a non-alloy-steel sleeve. The cell base is closed off by a "base plate", also made of non-alloy steel. A metal radiation-protection plug separates the cell head from the useful part. The cell head has a metal sleeve[1] (called the "insert"). The insert is partly backfilled with a swelling-clay plug and then sealed with a concrete plug to provide additional safety. This final configuration corresponds to the period after cell operation and sealing.

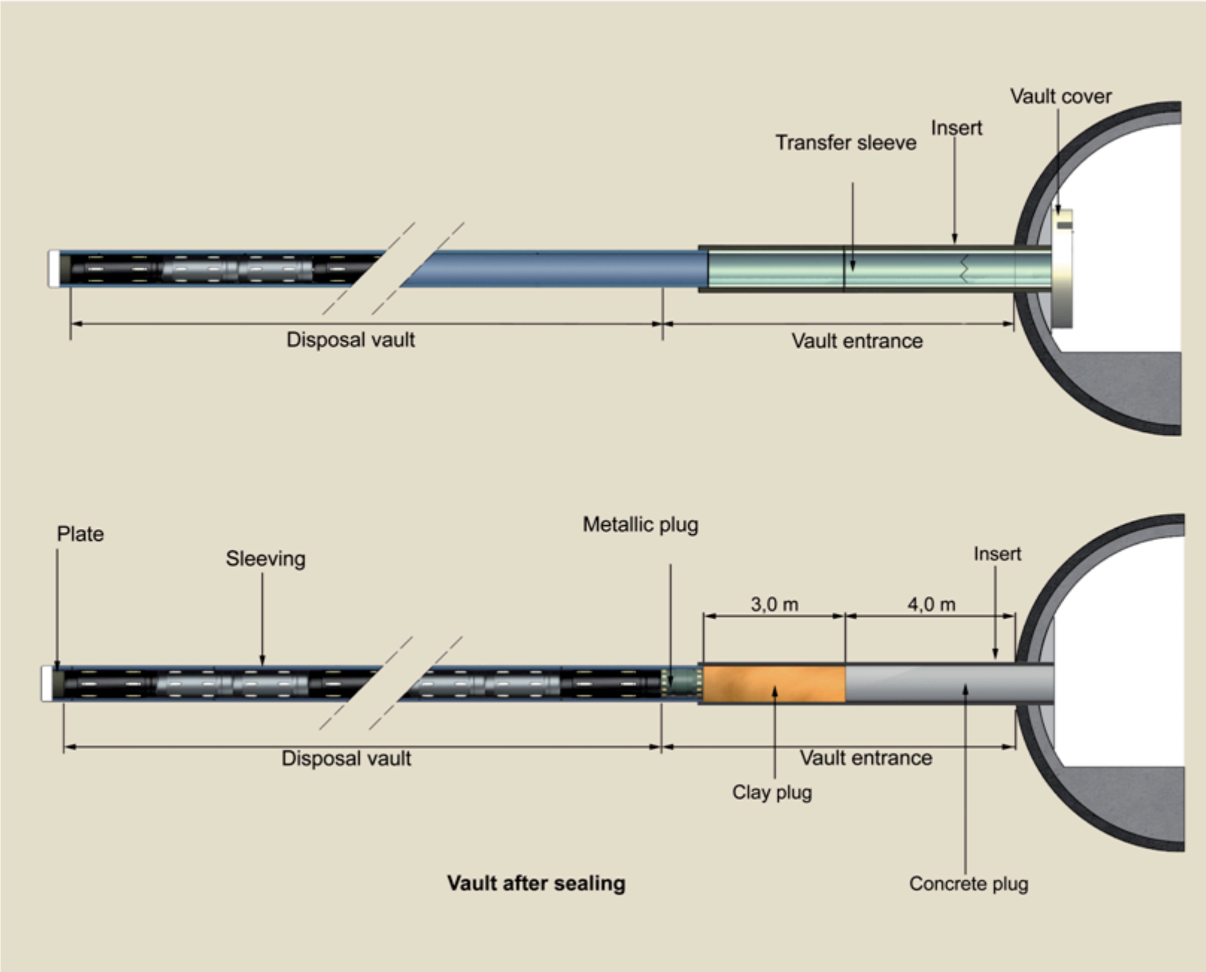

Figure 2 Schematic diagram of a HLW cell.

[1] The diameter of the sleeve for the useful part is smaller than that of the cell-head insert. This means it can slide in the insert. Thus, the effects of the thrust produced by its extension, which is a consequence of the heating by the exothermic packages, are absorbed without consequences for the cell head as a whole.

The useful part of the cell can receive about 20 moderately-exothermic packages (C0 packages) or 6 to 8 highly-exothermic packages. Highly-exothermic packages are spaced out using spacing buffers to ensure more uniform heat flows. The sleeve thickness, approximately 35 mm at 560 m depth, has been calculated to prevent the ground from loading the packages during the thermal phase. It also provides the operational clearance required for package removal during the reversibility period. The cell-head insert has also been designed to allow reversible operation of the cell.

1.2 Purpose of the “HLW cell” Programme Unit

The “HLW cell” Programme Unit has two main aims:

1) Check the technical feasibility of cell construction,

2) Provide partial answers to currently open science questions.

The technology aim consists of checking that it is possible to construct sleeved cells of approximately 700 mm diameter over lengths of 40 m (or 80 m or more) in the host formation. Answers are needed concerning the excavation (surface state of the cell walls, operating procedure specifications), sleeve installation (annular space that can reasonably be achieved, how sections are assembled) and managing expansion during the thermal stage of disposal (how the sleeve/insert sliding joint in the cell head operates).

The science issues in the "HLW cell" Programme Unit involve understanding the thermo-hydro-mechanical (THM) processes (and their characteristic time constants) at play on the sleeve’s extrados (outer sleeve surface) and the physical and chemical state of the argillites and the sleeve steel at this extrados.

The first phase aimed to check that it was possible to dig cells in several directions in the host formation, to test the excavation method (with or without advance casing) and to specify operating procedures for cell excavation in the next phases. It also provided initial data on the hydro-mechanical behaviour of the cells and their environment: the influence distance of the cells, their mechanical behaviour and damage around them. This phase ended in June 2010 and experience feedback is given in Section 2.1.

Phase 2, which started in June 2011 with a test for producing a cell head with an insert installed, also plans to produce a 40 m sleeved cell in 2011 to study how sleeve/argillite clearance reduces over time (resaturation kinetics, sleeve loading) and its influence on the mechanical behaviour of the sleeve. Initial Phase-2 experience feedback is given in Section 2.2.

1.3 Purpose of Phase 3.1 of the “HLW cell” Programme Unit

Phase 3.1 studies the behaviour of a HLW cell under thermal loading by simulating the heat produced by waste packages. The aim is both to demonstrate production and operation of a “HLW cell” and to understand the THM behaviour of the neighbouring rock.

For this, the experimental concept must be representative of a real disposal cell so that the operation of a HLW cell can be demonstrated for “C0” waste (packages installed without spacing buffers) and its impact on its environment studied. In detail, the main aims for Phase 3.1 are:

- production of a cell that includes:
    - the cell body that corresponds to the useful part, fitted with a rigid sleeve,
    - the cell-head insert,
    - installation of a cell base plate,
    - installation of a plug at the head of the useful part (representing the bioshield),
    - installation of a cover plate at the insert head,
- study of cell behaviour under thermal loading:
    - the mechanical behaviour of the sleeve and insert,
    - cell head operation (cell body expansion and sliding in the insert),
- study of the impact of the thermal gradient along the cell on the behaviour of the access drift,

- analysis of the THM behaviour of the rock/sleeve interface and its impact on the (uniform or non-uniform) mechanical loading of the sleeve.

This experiment will also be used to study the THM behaviour of the argillite beyond the interface, mainly in terms of the overpressure induced by the heating phase. The data acquired could also be compared with that from the smaller-scale ("TER" and "TED") thermal experiments, in particular using computer simulations based on the THM models defined in these experiments. In this context, the cell heating test will contribute to checking the ability of these THM models and other models (in terms of their representation of phenomena, parameters etc.) to represent the THM behaviour of "distant field" argillites in association with the THM behaviour of the rock/sleeve interface.

To fulfil these aims, Phase 3.1 involves producing a 25-metre-long cell, comprised of a cell head and a useful part, with a heating device installed in the useful part over a 15 m length (between 10 m and 25 m) to simulate waste package heat. The experimental concept is described and substantiated in the next section.

Note: The "demonstration test" part, i.e. the demonstration of cell construction and operation in Phase 3.1 (along with the insert test performed in Phase 2) are part of the European LUCOEX project. The THM analysis of the interface, which is of a more R&D nature, is not part of the European project.

2. Experimental strategy

2.1 Experience feedback from Phases 1 and 1b of the "HLW cell" Programme Unit

Phase 1 was performed in the first half of 2009 in the *Galerie de Recherche et Méthode* (GRM, research and method drift), while Phase 1b was performed in the first half of 2010 in the *Galerie d'Accès Nord* (GAN, north access drift).

From a technology standpoint, the Phase 1 experience feedback highlighted the necessity to modify the equipment, the excavation operating procedures and the geometry of the sleeve sections to be able to produce a 40 m sleeved cell, which corresponds to the ANDRA concept for HLW-LL disposal, and to make the maximum improvement to the cut quality and the state of the cell wall, in order to produce an annular space that is as regular as possible.

These modifications were implemented for Phase 1b and showed that a 40-metre-long sleeved cell could be produced. It should be noted that the sleeve was flexible (socketed sections with free play, in contrast to Phase 1 where the sections were welded). This prevented any blocking in the ground despite a path deviation of more than one metre, due to the failure of a cutting head guide runner. Production of an unsleeved 20 m cell showed that these modifications also significantly improved the state of the cell wall (much smoother overall, avoiding the "corrugations" seen in Phase 1, see Figure 3) The formation of breakouts, which are induced by the natural stress field and lead to overprofiles mainly at 45° in the upper arch for cells orientated along the main horizontal stress, is inevitable, but their extent is reduced (Figure 4).

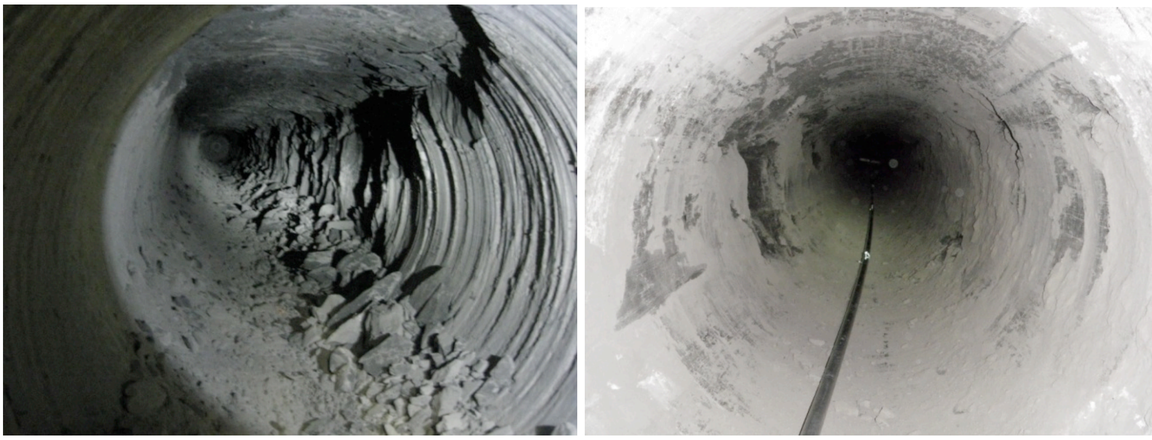

Figure 3 State of the cell walls for ALC3005 (Phase 1, left) and ALC1603 (Phase 1b, right).

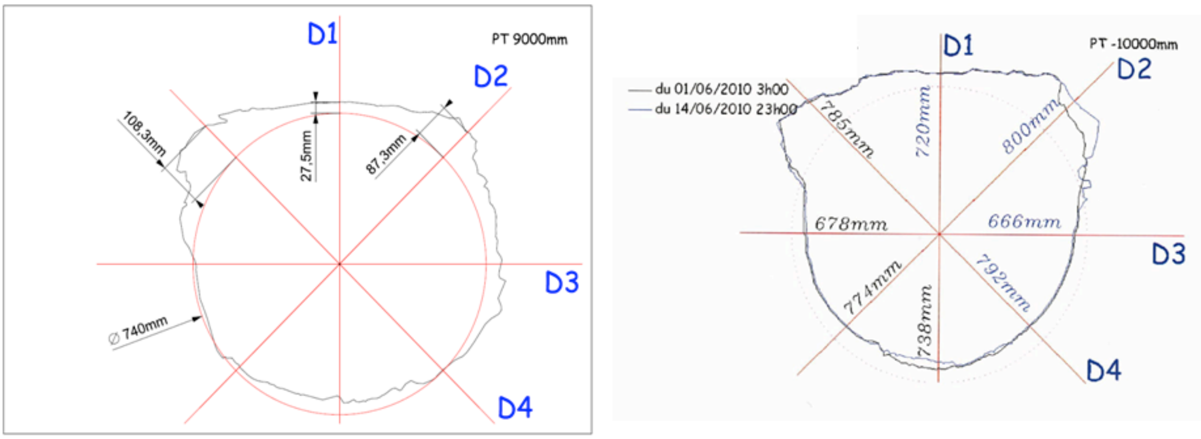

Figure 4 Example of overprofiles measured at 9 m in cell ALC3005 (Phase 1) and at 10 m in cell ALC1603 (Phase 1b).

From a science standpoint, Phases 1 and 1b have shown that the overpressures produced during cell excavation and measured in a horizontal plane are much higher than the values from the model, both in terms of amplitude and influence distance. The thermal impact associated with advance of the working face, of the order of 8°C at 5 cm from the cell wall (measured during ALC1601 cell excavation in Phase 1b), does not, in itself, explain these high overpressures. Other factors, such as the pressure of the cutting head on the working face (not taken into account in the models) and anisotropy of mechanical behaviour, could be the source of the discrepancies observed between the measurements and the computer-model predictions.

Furthermore, convergence measurements taken in Phases 1 and 1b (mainly on the two bare cells ALC3005 in Phase 1 and ALC1603 in Phase 1b) provide an order of magnitude for the closing of the annular gap. Figure 5 Convergences measured on 4 diameters of the section at 12 m in the ALC1603 cell (Phase 1b), over the first 10 months of measurement.Figure 5 shows the convergences, measured on 4 diameters at 45° at 12 m depth in cell ALC1603 (20 m long, Phase 1b), for the first 10 months of measurement (note: measurements in this cell only started 3 weeks after excavations to allow for the performance of damage measurements). It can be seen that horizontal convergence is much larger than for the other diameters and that vertical convergence is the smallest[2].

[2] Note that the presence of overprofiles associated with the formation of breakouts can affect the amplitude of the measured convergences because some sensors are not in contact with the rock and so do not react immediately to wall convergence; this was the case for the 45° diameters on cell ALC1603 where the convergences should be larger.

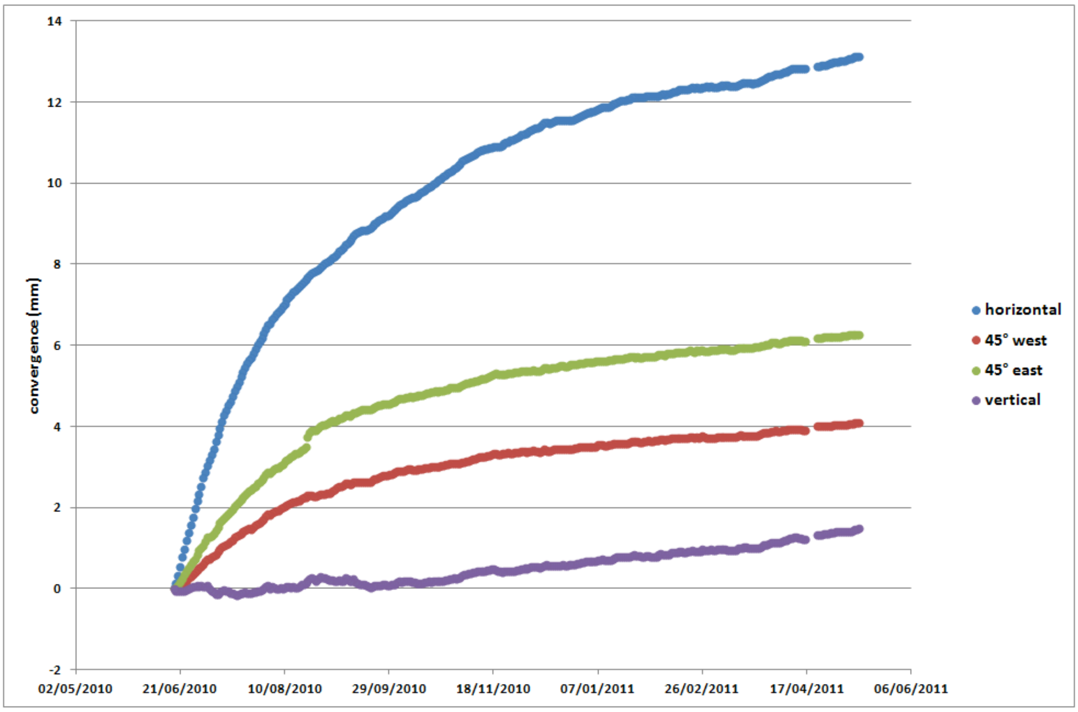

Figure 5 *Convergences measured on 4 diameters of the section at 12 m in the ALC1603 cell (Phase 1b), over the first 10 months of measurement.*

The maximum convergences, taken for the majority (75%) of measurement sections on the horizontal diameter for the two bare cells fitted with instruments (which were orientated along the major horizontal stress), generally seem to increase as a function of depth up to a plateau beyond 6 m (if the point at 16 m is excluded), which is consistent with changes in the state of stress in the tunnel wall (Figure 6).

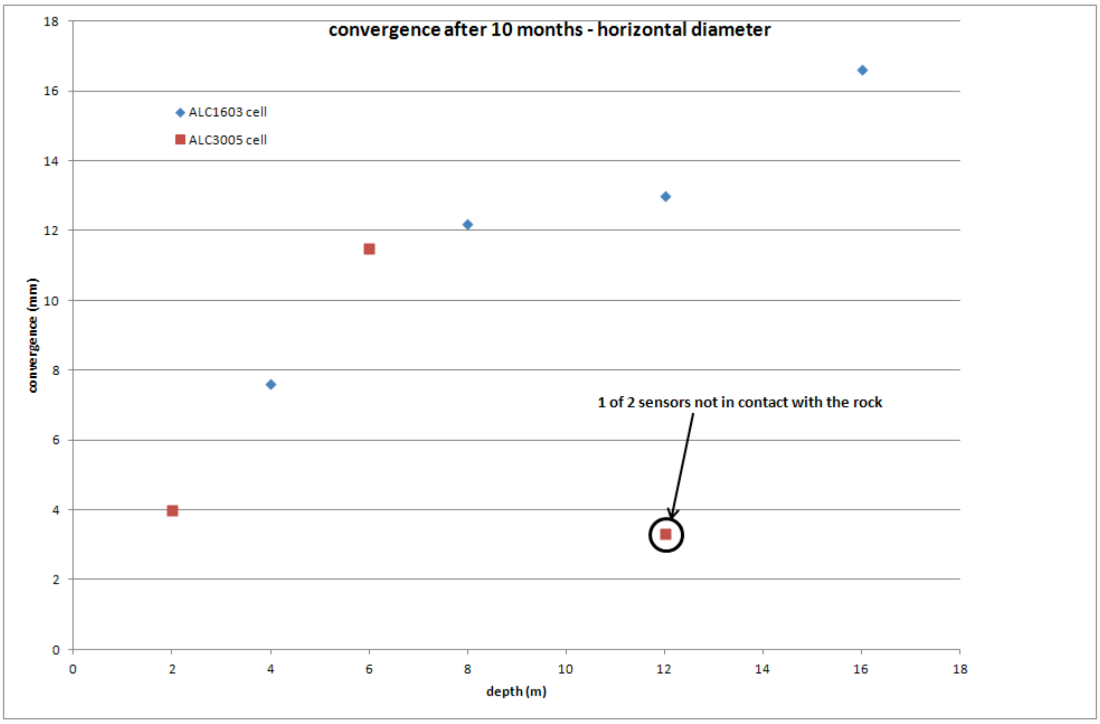

Figure 6 *Horizontal convergence measured on various sections of the cells fitted with instruments; the section at 9m of cell ALC3005 has not been used (influence of spalling on the measurement).*

After 10 months of measurements, the (diameter ratio) convergence rates varied from 10^{-10} s^{-1} to 10^{-11} s^{-1}, for the two bare cells fitted with instruments (Table 1). The convergence rates after 22 months of measurements (only for ALC3005, Phase 1) were of the order of 10^{-11} s^{-1}, which confirms the decrease in rate over time.

Table 1 *(Diameter ratio) convergence rates at 10 months for cells ALC3005 (Phase 1) and ALC1603 (Phase 1b) and at 22 months for cell ALC3005*

diameters	12 m - ALC1603	16 m - ALC1603	8 m - ALC1603	4 m - ALC1603		12 m - ALC3005	9 m - ALC3005	6 m - ALC3005	2 m - ALC3005
	convergence speed (per second on 1 month) after 10 months								
vertical	1,40766E-10	1,56406E-10	8,86303E-11	2,08542E-11		7,29897E-11			0
45° west				4,17084E-11				1,40766E-10	5,7349E-11
horizontal	1,77261E-10	1,6162E-10	6,77761E-11	0			8,86303E-11	1,35552E-10	5,7349E-11
45° east		2,24183E-10		3,64948E-11					
	convergence speed (per second on 1 month) after 22 months								
vertical						1,04271E-11			0
45° west								4,69219E-11	5,21355E-12
horizontal							-5,7349E-11	5,21355E-11	2,08542E-11
45° east									

This data demonstrates that, for an initial annular spacing of 20 mm, the rock mass may take several years to come into contact with the sleeve and this will not be the case when the heater element is activated in Phase 3.1. However, as creep rate is temperature dependent, heating may then accelerate rock mass convergence and its coming into contact with the sleeve. Data from the "TEC" experiment (behaviour of a metal casing fitted with instruments in a standard diameter borehole and subject to thermal expansion), launched in February 2011, will be used to help understand the thermo-mechanical behaviour of the sleeve. Similarly, monitoring of the mechanical behaviour of the sleeve fitted with instruments on the 40 m cell of Phase 2 of the "HLW cell" Programme Unit, which will be performed in September/October 2011, will contribute significant experience feedback.

2.2 Initial lessons from Phase 2 of the "HLW cell" Programme Unit

Phase 2 of the "HLW cell" Programme Unit was launched in June 2011 by test production of a cell head with a 10 m insert installed. The test characteristics were as follows:

- excavation diameter: 791 mm,
- outer diameter of insert: 775 mm; inserted as excavation proceeded, with an 8 mm annular space,
- insert thickness: 35 mm,
- insert assembled from welded 2-metre-long sections.

After 7.5 m of excavation (7.1 m in the argillite), the thrust forces required to install the insert reached the maximum capacity of the machine (160 tonnes). This led to the decision to stop excavation to avoid the risk of jamming when driving the last insert section into place. Visual inspections performed after the machine was removed showed that the cell-wall/insert annular space was almost non-existent.

This test showed that, under the conditions specified for Phase 2, there is significant risk of the insert jamming before 10 m is reached. Consequently, the insert configuration must be modified for Phase 3.1 to minimise the risk of jamming during excavation (cf. Section 2.4.1.1).

At the time of writing, production of a 40-metre-long cell with a sleeve fitted with instruments is planned for September/October 2011.

2.3 Modelling

ANDRA (DRD/EAP department) has produced computer models to help in the preliminary design of the experiment, in particular for:

- substantiating that 15 m of heating is representative with respect to the baseline concept where packages are inserted over 30 m,
- checking the effects of the sleeve-head plug and the base plate on heat distribution in the cell, taking into account various assumptions regarding the heater element's outline dimensions (its diameter and whether it is centred in the sleeve or placed on the sleeve's invert),

- preliminary design of the heating cycle and the power required,
- studying the impact of the thermal gradient along the cell on the GAN access drift.

The calculations were performed for a 5-year thermal transient with a thermal peak at 2.5 years, and for a shorter transient corresponding to an increase of 4°C per month.

2.3.1 Representativeness of applying heating over 15 m

Figure 7 shows various longitudinal thermal profiles in the argillite wall along the useful part of the cell and Figure 8 shows radial thermal profiles in the argillite at the middle of the useful part of the cell. Both figures give data for:

- a cell with a 15-metre-long useful part,
- a cell with a 30-metre-long useful part,
- a cell with a 30-metre-long useful part in the context of a repository (taking into account the presence of neighbouring cells and their overlapping thermal fields).

To facilitate comparison, the longitudinal profiles for the two cases where the cell has a 30-metre-long useful part have been scaled to a length of 15 m (as the variation in the thermal profile is mainly seen near the two extremes of the useful part). Comparison of the longitudinal profiles shows that a 15-metre-long useful part is highly representative of a 30-metre-long useful part in the central section, with less than 2°C of discrepancy in the argillite wall between 4 m and 11 m. The discrepancy reaches up to 4°C in the argillite wall towards the ends of the useful part, i.e. between 0 and 4m and 11 m and 15 m. On the other hand, the radial profiles in the middle of the useful part are extremely similar for useful-part lengths of 15 m and 30 m.

Naturally, comparison with the case where the cell has a 30-metre-long useful part under repository conditions shows differences associated with the presence of neighbouring cells, which cannot be reproduced in the experiment.

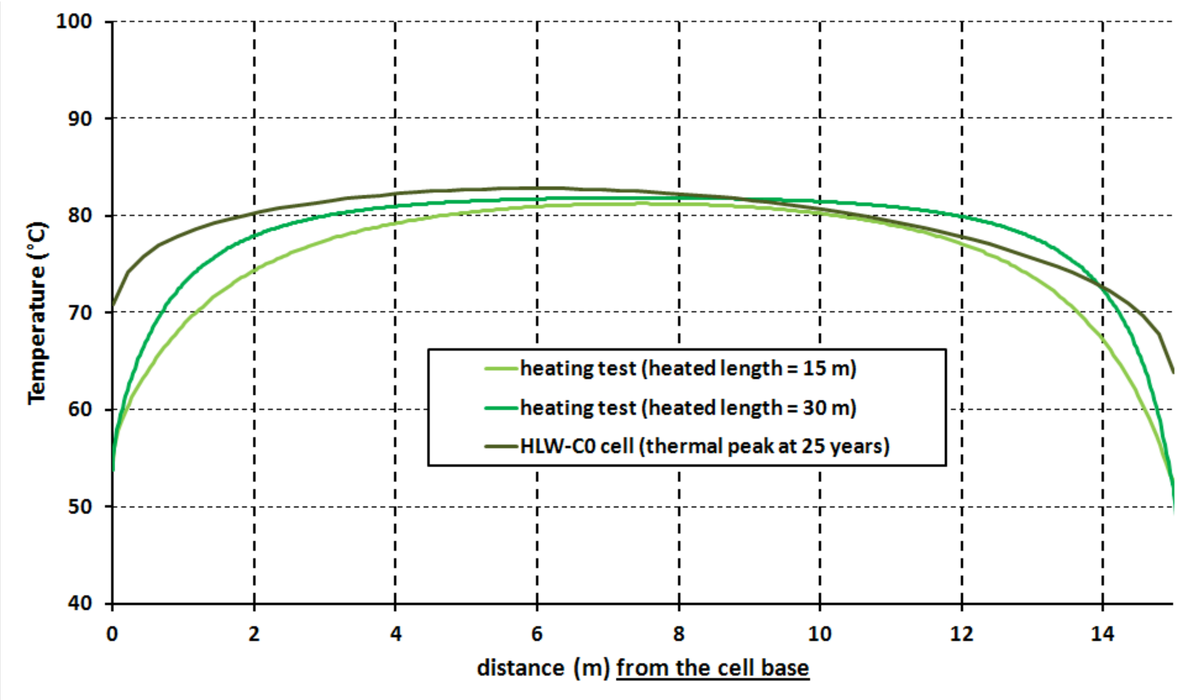

Figure 7 Temperature profile in the argillite wall along the useful part of the cell at the moment of thermal peak

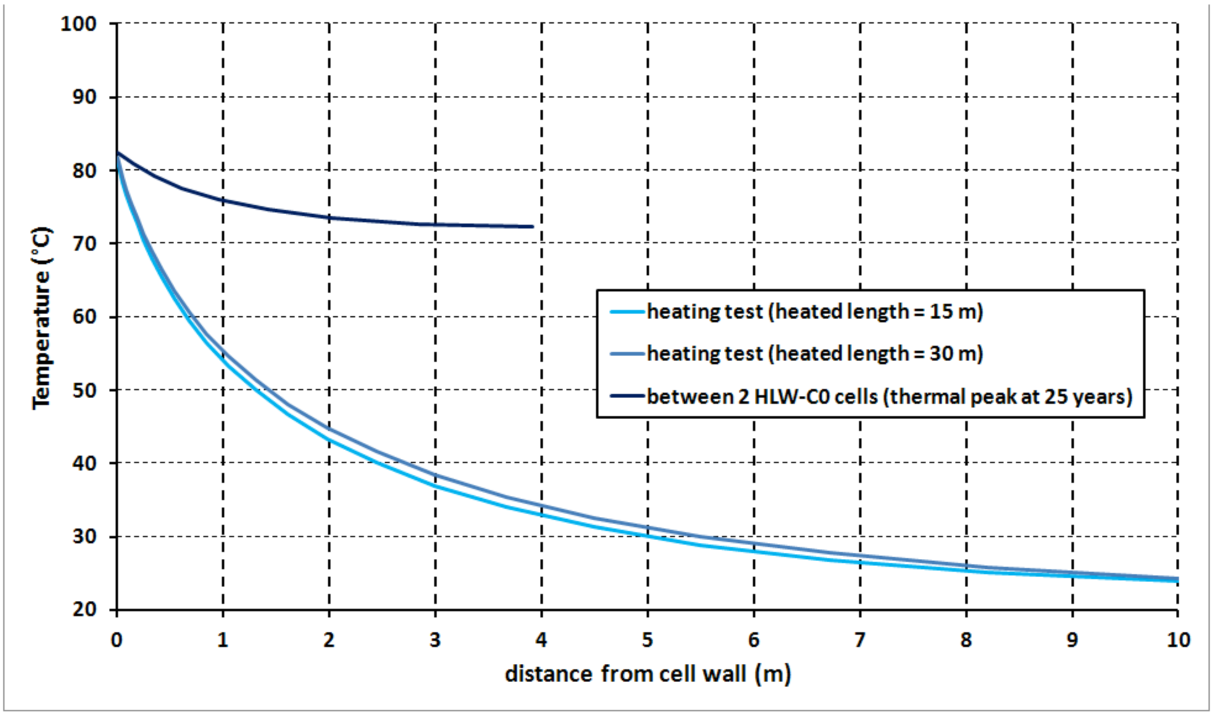

Figure 8 *Radial temperature profile in the argillite at the middle of the useful part at the moment of thermal peak*

2.3.2 Effect of the dimensions and position of the heating element

Figure 9 gives the circumferential temperature profile inside the sleeve of the useful part of the cell, for an argillite/sleeve clearance of 20 mm, using various assumptions regarding the diameter and position of the heating element in the sleeve (centred or lying on the sleeve's invert). The results show that the diameter of the element has a negligible effect (test cases: element diameter 56 to 63 cm, element lying on the sleeve's invert).

Having the element off-centre, lying on the sleeve's invert, produces temperature differences as high as 5°C between invert and crown at the outer wall of the sleeve. Installation of ceramic runners under the heater element, which is planned for the experiment, should limit these temperature differences by preventing direct contact between the heater element and the sleeve, while also providing greater representativeness with respect to the repository concept (as the packages have ceramic runners).

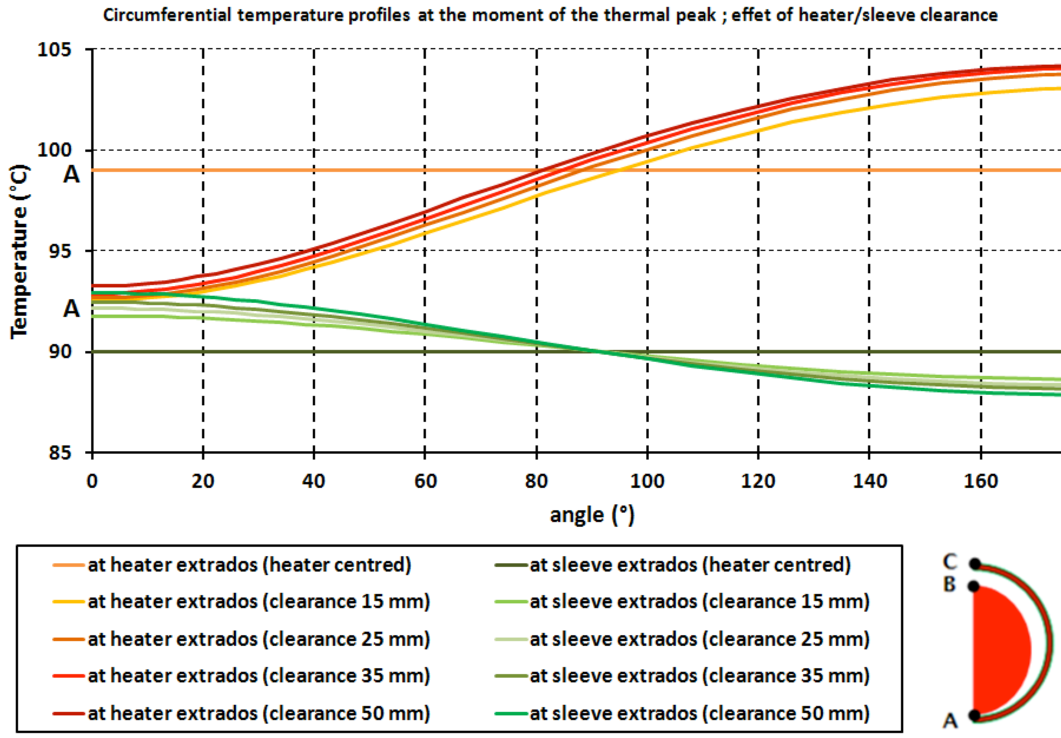

Figure 9 *Effect of the dimensions and position of the heating element*

2.3.3 Effect of the useful part's head plug and base plate

The effect of installing the useful part's base plate and head plug on the thermal profile along the useful part of the cell is negligible, as shown in Figure 10.

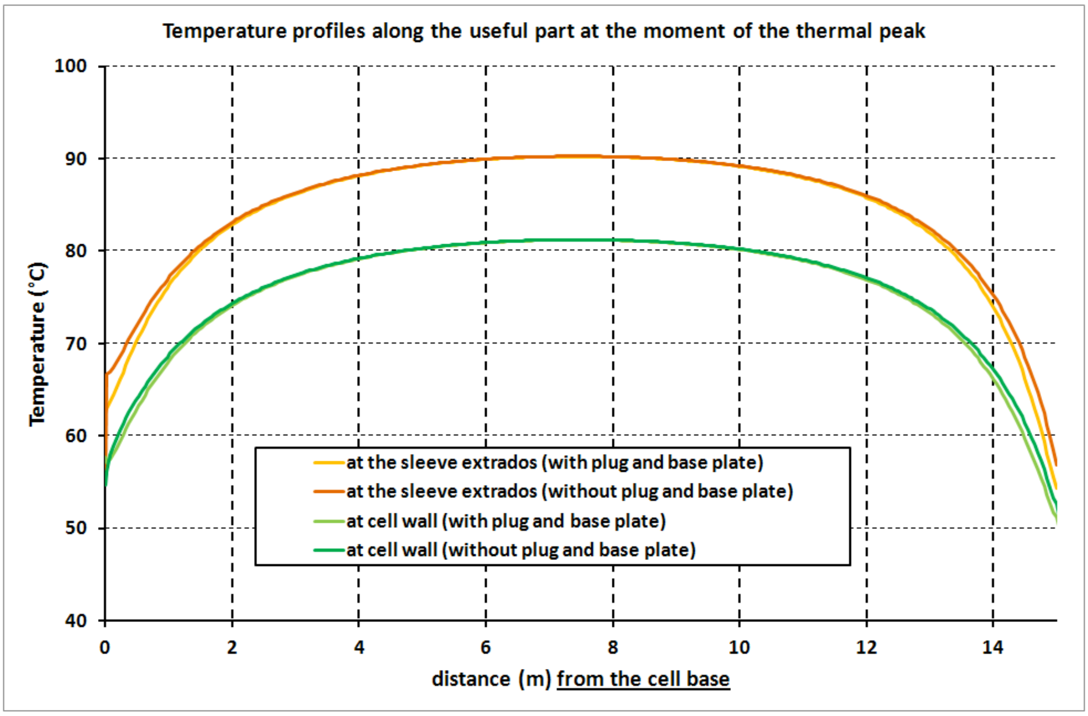

Figure 10 *Effect of the head plug and base plate of the useful part on the temperature profile along the useful part of the cell.*

2.3.4 Preliminary design of the thermal load

Evidently, a thermal cycle that is representative of the repository concept (thermal peak at 25 years for C0 waste cells) cannot be reproduced for Phase 3.1, which needs results in a reasonable time-frame.

However, in order to be representative of the waste packages and of the thermal loading of a cell and its near-field argillites in the (very) short term (in particular before significant thermal interaction with other cells), a rated power of approximately 100 W per metre (between 10 m and 25 m) is to be applied from the time that heating begins. Ultimately, the models should be able to set this value more precisely by taking into account the geometrical differences between the experimental concept and the repository concept.

2.3.5 Effect of the thermal gradient along the insert on the GAN access drift

Simulations performed on the thermal impact of the cell on the access drift show that the temperature rise in the access drift is small (Figure 11) and remains well below the annual temperature variations associated with drift ventilation. The temperature of the drift by the cell never exceeds 25°C (for an initial temperature of 22°C).

On the other hand, the thermal gradient along the insert (Figure 12) could induce additional stress into the shotcrete, estimated at 0.4 MPa. Thus, it is important to monitor the strain induced in the access drift by this thermal gradient.

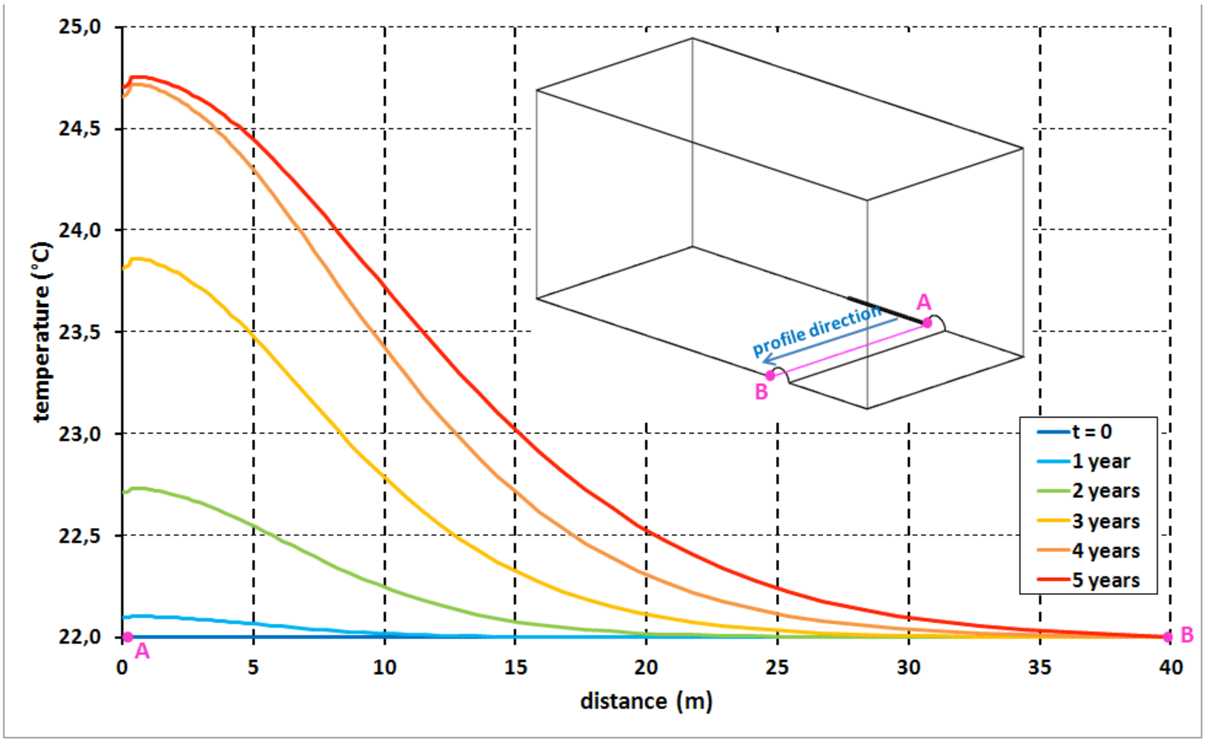

Figure 11 Temperature increase in the GAN access drift (assuming a temperature of 90°C at the sleeve extrados at two-and-a-half years).

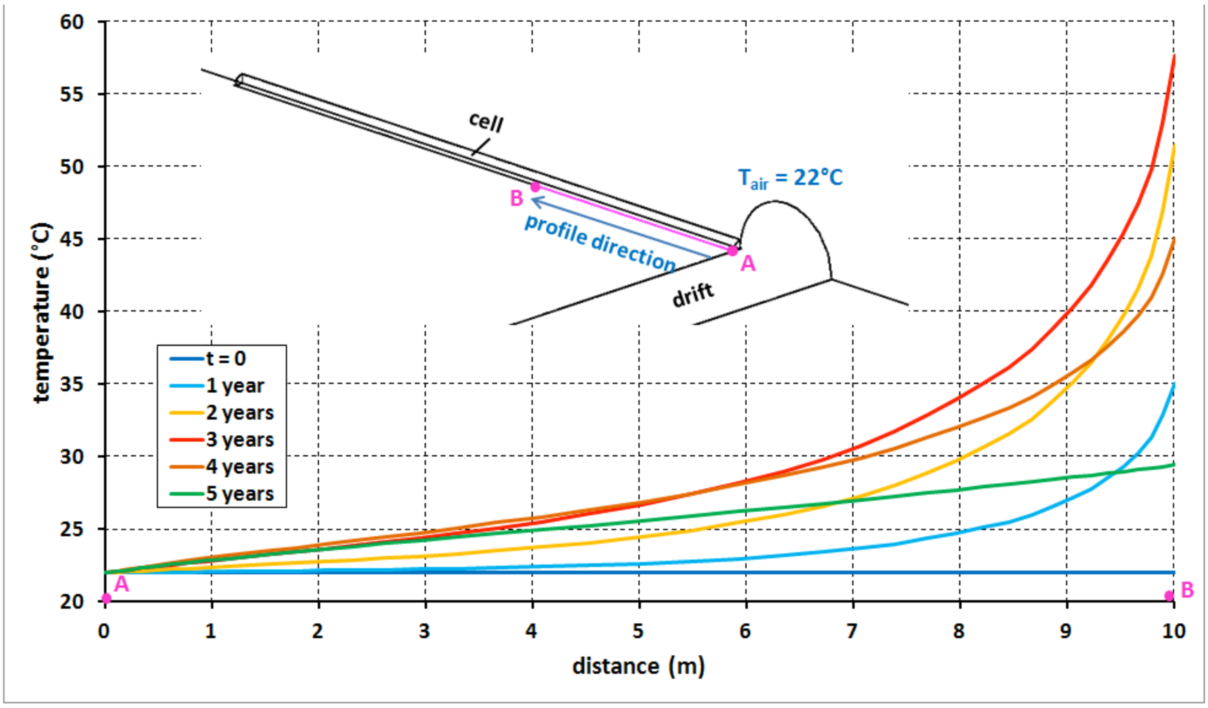

Figure 12 *Temperature gradient along the insert, for a given temperature of 22°C in the GAN access drift (assuming a temperature of 90°C at the sleeve extrados at two-and-a-half years).*

2.4 Design of the experiment

Phase 3.1 of the "HLW cell" Programme Unit includes the production of a single 25-metre-long demonstrator cell. This cell is to be located in the GAN drift (Figure 13). Peripheral boreholes are to be drilled from the GAN drift and from the NRD niche located in the GRD drift (Figure 15).

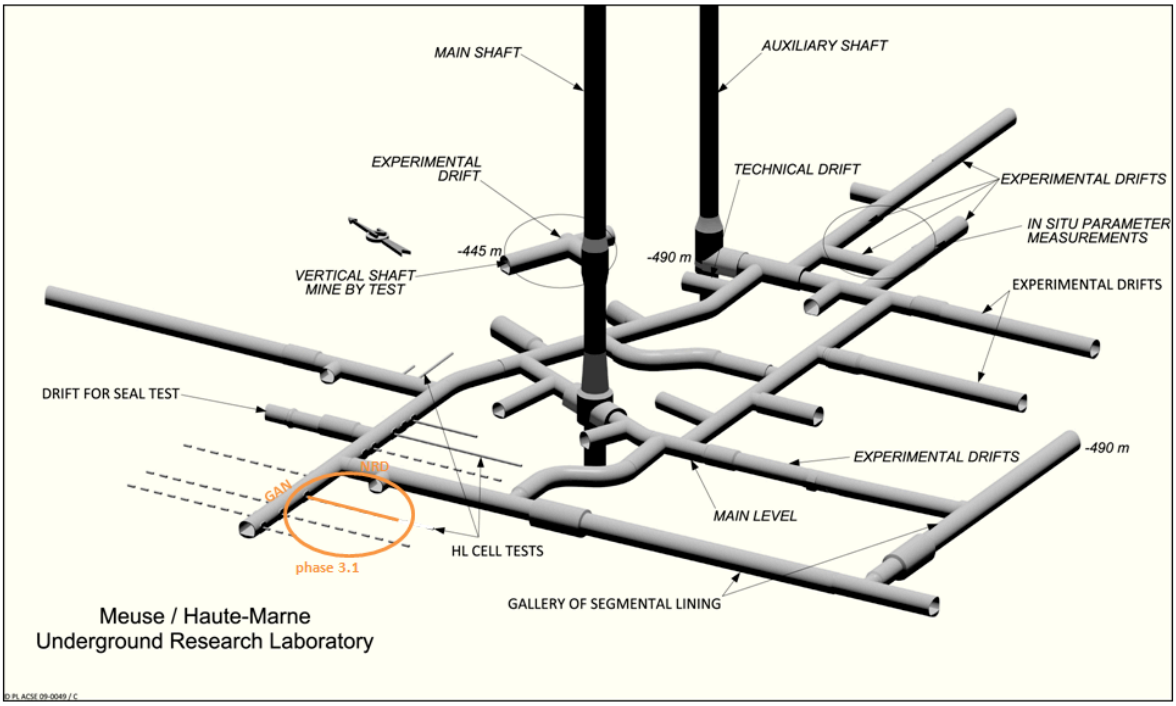

Figure 13 *Location of Phase 3.1 of the "HLW cell" Programme Unit*

2.4.1 Cell characteristics

The aim is to produce a cell that includes the various elements that comprise a repository cell as per the ANDRA reference concept:

- the cell-head insert,
- the cell body that corresponds to the useful part, fitted with a rigid sleeve,
- a cell base plate,
- a plug at the head of the useful part (representing the bioshield),
- an insert-head cover plate.

2.4.1.1 Insert

The initial lessons from Phase 2 show that, if produced under the same conditions (see Section 2.2), there is a significant risk of the insert jamming during cell-head excavations. For this reason, the cell-head configuration for Phase 3.1 shall be modified and have the following characteristics:

- cell-head length limited to 6 m,
- annular space increased to 10-12 mm width (compared with 8 mm during the Phase 2 test).

As for Phase 2, the insert is to be assembled from 2 m sections welded together. Use of welding must take into account the presence of sensors on the insert (risk of damaging the instrumentation). The thickness of the insert must be less than for Phase 2 (where it was 35 mm), approximately 25 mm, to allow the insertion of the sleeve of the cell's useful part (which has an outer diameter of 700 mm).

2.4.1.2 Useful part

The useful part of the cell is to be similar to that produced during earlier phases: excavation to a diameter of 740 mm, sleeve with a 700 mm outer diameter and 20 mm thick. The aims of the thermo-mechanical measurements require that an annular space of 20 mm radius be retained if possible (to be validated following experience feedback from Phase 2) to give sleeve/rock mass contact in a reasonable time-frame. The useful part is to be 19 m long, but only the last 15 metres (between 10 m and 25 m depth) are to be heated to maintain a distance of 10 m to the GAN access drift, which is representative of the repository cell concept.

However, the assembly mode for the sections is to be different in order to ensure sleeve rigidity. The sleeve must be rigid so that its extension under thermal loads can be absorbed by the insert (by sliding) without consequences for the cell head (see Part 1, Section 1.1). At the date of writing, it is planned that the sleeve sections will be welded together in the useful part, with simplified sockets but better bearing surfaces to ensure alignment (10 two-metre-long sleeves, with 1 m overlap between the useful part and the insert; the three other sleeve sections, which only serve to push the sleeve train at the insert, are not to be welded so that they can be removed after excavation). The decision whether or not to use welding must take into account the presence of sensors on the sleeve (risk of damaging the instrumentation).

On the other hand, in contrast to Phase 2, the Phase 3.1 sleeve does not need to be leaktight.

Modelling has shown that a heating length of 15 m is representative of the thermal behaviour around a cell with 30 m useful part (that complies with the concept), except towards the two ends where there is a discrepancy of a few degrees. This shortening of the useful part for the experiment, reduces the heating power required and makes the installation of instrumentation and equipment easier.

2.4.1.3 Base plate

As for Phase 2, a base plate is to be installed at the base of the useful part (Figure 14). However, Phase 3.1 has no leaktightness constraint. Depending on experience feedback from Phase 2, the design of the base plate and its seating on the lead sleeve section will be reused or modified for Phase 3.1.

Figure 14 *Base plate during Phase-2 installation tests*

2.4.1.4 Plug at the head of the useful part

Modelling has shown that the impact of the head plug on the temperature profile along the useful part is negligible. Thus, its thickness can be limited to make it easier to install, and the plug can be just a simple steel plate. This plate is to have a hole in its centre to allow instrument cables from the useful part to pass.

2.4.1.5 Insert-head cover plate

The insert-head cover plate shall also have a hole in its centre to allow instrument cables from the useful part and the insert to pass. It shall also be fitted with a collection and drainage system for water that may flow inside the cell (as the sleeve is not leaktight, water from the formation could flow in the insert).

2.4.1.6 Specific issue for the plug and cover plate

The installation of the plug at the head of the useful part and the insert-head cover plate will limit or prevent gas exchanges between cell and drift. Under these conditions, the risk of an explosive atmosphere forming cannot be excluded (see also Part II, Section 1.1).

This risk must, therefore, be taken into account when designing the plug at the head of the useful part (with a view to dismantling the heating device) and the insert-head cover plate (with a view to intermittent inspections of the overlap area), so that the internal atmosphere can be measured or treated before operations in the insert (for example, by inert-gas flushing).

2.4.2 Description of the experimental set-up

The experimental set-up for Phase 3.1 of the “HLW cell” Programme Unit is comprised of:

- a heating element, that simulates the heat produced by C0 waste packages over a 15 m length;
- instrumentation for the useful part of the sleeve, to study sleeve strain under thermal load (strain gauges, measurement of elongation and temperature) and to study changes in the annular space between cell wall and sleeve (total pressure or load on the sleeve and displacement sensors to measure the reduction in annular clearance). This instrumentation shall be supplemented by sensors integrated into the heating element (sleeve convergence, temperature and inclinometers);
- instrumentation for the insert, to study insert strain (strain gauges, convergence), measure the relative movement of the sleeve in the insert and measure the thermal and relative humidity gradients along the insert;
- peripheral instrumentation, in peripheral boreholes and in the access drift, to follow both the THM impact of the heated cell on the surrounding rock mass – in particular to highlight overpressures induced by the heating – and the impact of the thermal gradient on the drift around the insert.

Figure 15 Overview of the experimental set-up for Phase 3.1 of the "HLW cell" Programme Unit

gives an overview of the experimental set-up for Phase 3.1 of the "HLW cell" Programme Unit.

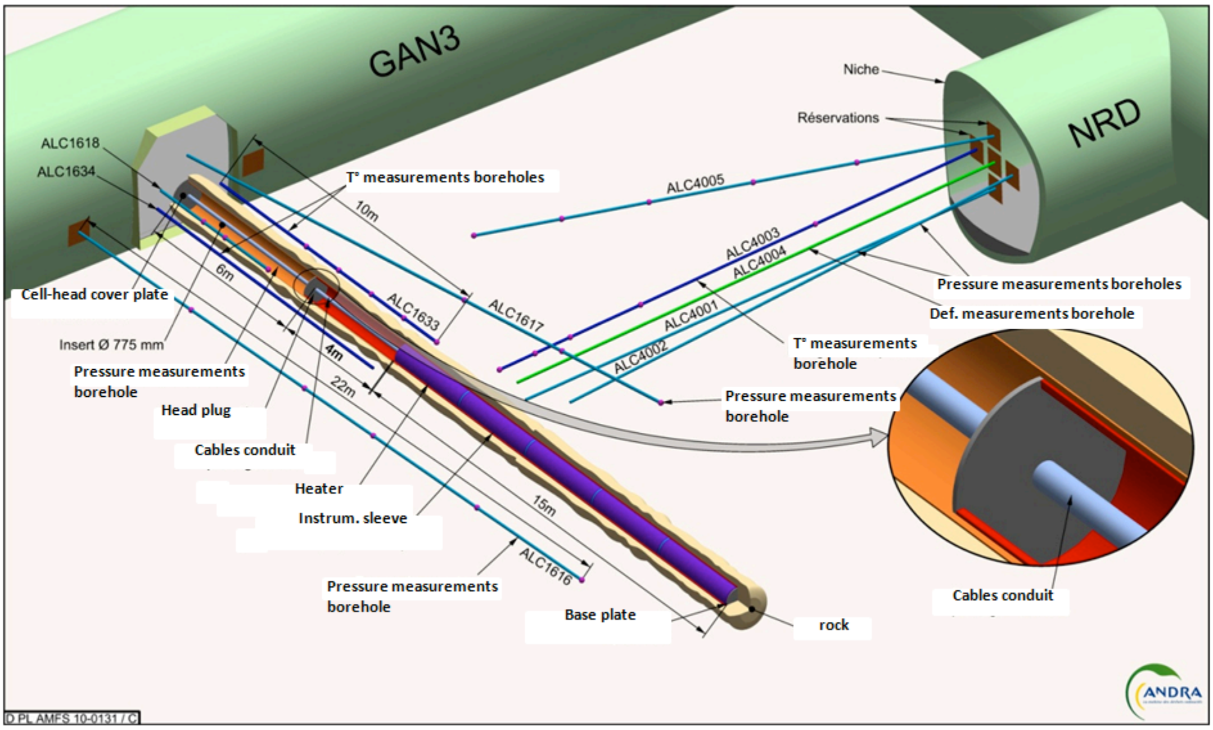

Figure 15 Overview of the experimental set-up for Phase 3.1 of the "HLW cell" Programme Unit

The Phase 3.1 sleeve and insert instrumentation has many points in common with the Phase 2 sleeve instrumentation and will pose similar problems (such as insertion of sensors into the sleeve, cable routes and installation procedures). Phase 2 experience feedback will, therefore, be very important for performing Phase 3.1 (in particular with regard to instrumentation design and the interfaces between the various operators).

As the sleeve is not leaktight, the instrumentation and the heating element must be leaktight.

3. Description of the equipment and associated measurements

3.1 Heating element in the useful part

3.1.1 Heating element specifications

The heating element specifications are as follows:

- the heating shall be performed on a 15 m length between 10 m and 25 m depth in the cell;
- due to drift dimensions, the heating element is to be introduced into the sleeve in sections. Nevertheless, the heating shall be continuous over the 15 m;
- the heating device must provide good radial uniformity of temperature;
- the heating device shall have a maximum diameter of 60 cm (to allow for installation of sleeve instrumentation);
- the element shall be placed on the sleeve's invert (Figure 16), on runners (three sets of two runners per section) so that the device is not in direct contact with the sleeve (runner thickness

must be appropriate to the diameter of the device so as to allow installation of sleeve instrumentation). If possible, the thermal conductivity of the runner material shall be similar to that of ceramic (approximately 40 W/m/K at 20°C);

- the cell sleeve will not be leaktight, so water could reach the inside, especially at the sleeve joints. For this reason, the heating device must be completely waterproof. It must be leaktight both for liquid water and steam (as the heater element could reach temperatures above 100°C);
- the control system must allow heating and cooling cycles, both slow and fast, stepwise and smooth, at a set power or temperature; thus, the device should be resistant to these heating and cooling cycles (10°C - 150°C).
- the maximum temperature at the sleeve wall shall be 90°C, so the device must be able to attain this temperature under optimum conditions with a margin of over 15-20%;
- the device must be designed to be reliable over several years of heating. The design must therefore include:
  - ✓ a back-up system that allows heating to continue if the main system fails,
  - ✓ the possibility of repairing the equipment in the event of failure. Such operations must be possible without removing the heating device.

The experiment's thermal cycle shall be designed to be representative of the heat released by waste packages (see Section 2.3.4). The power shall be controllable, and a power of 100 W per metre shall be available (to be clarified by modelling during device design) from the beginning of heating. An initial short, low-power heating cycle may be necessary to ensure correct operation of the heating device. It must, therefore, be checked that the time required for the overpressure created in the argillites by this initial cycle to dissipate before operating at rated power is not too long. The power could then be adjusted depending on the temperature measured on the internal wall of the sleeve.

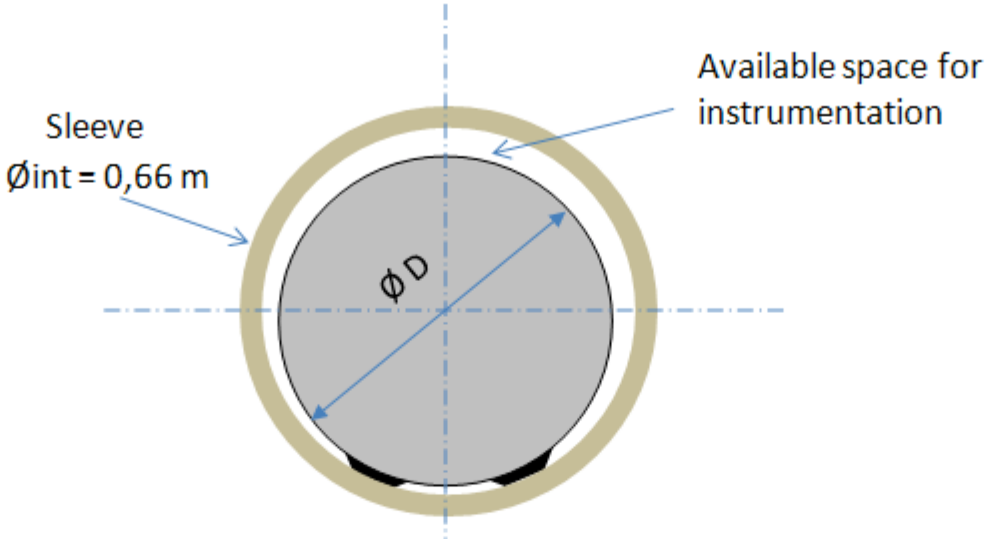

Figure 16 *Schematic diagram of the heating system placed on the invert of the useful part's sleeve.*

3.1.2 Heating system instrumentation

3.1.2.1 Temperature measurements

Sensors integrated into the heating device shall monitor the heating system temperature (four-wire platinum Pt100 or Pt1000 probes are recommended). At least 45 temperature sensors shall be located on the outside of the heater element, for example placed in two groups at 1 m and 2 m along the 3 m section, and spaced at 120°. The measurement uncertainty shall be less than 0.1°C for a measurement range of at least 0 - 150°C.

3.1.2.2 Convergence measurements

The heating and mechanical loading of the ground will lead to variations in the diameter of the cell sleeve; a system for measuring these variations (convergence or divergence) in sleeve diameter is to be installed. These convergence (or radial displacement) measurements shall be located at or by the annular clearance measurements planned in the sleeve instrumentation (see Section 3.2.6). The measurement uncertainty should be less than 0.05 mm and the measurement range should be at least 15 mm.

3.1.2.3 Inclinometer measurements

Sleeve strain caused by heating could lead to heating system movements. To monitor and quantify these movements, inclinometers shall be installed on each heater element section. These inclinometers can also be used to check the alignment of the sections on installation and will provide information on the appearance of alignment faults during the test. The measurement uncertainty shall be less than 0.1 µm/m.

3.2 Instrumentation on the cell's useful-part sleeve

3.2.1 Measurement of local strain

The purpose of this measurement is to assess the main characteristics of the rock-mass load and the impact of the thermal load on the sleeve. It involves measuring axial and orthoradial strain on various parts of the sleeve. Three sections (labelled 2, 4 and 6 in Figure 17) shall have instrumentation fitted. Each of these sections shall be fitted, on its internal surface and as near as possible to its central part (depending on accessibility), with strain gauges (extensometers). These shall be placed evenly around the pipe in 6 measurement areas, two of which shall be located on the horizontal diameter (see Figure 18). The measurement uncertainty shall be less than 10 µm/m.

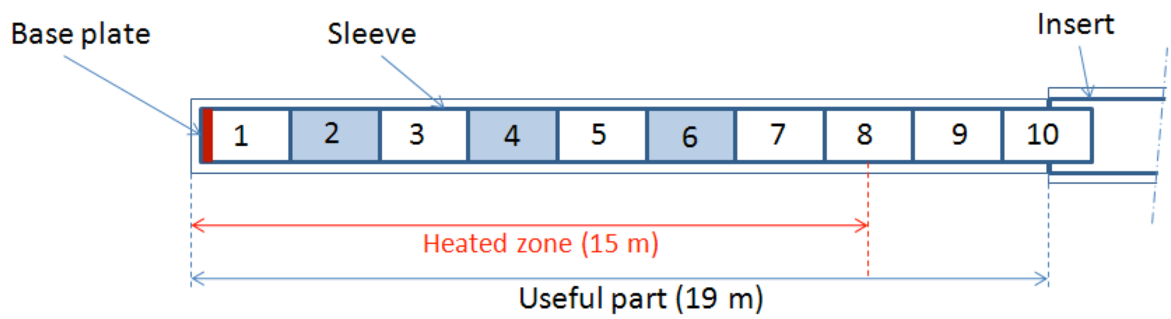

Figure 17 Useful-part sleeve – the sections fitted with instrumentation are shown in grey

3.2.2 Measurement of the sleeve's mean axial strain

The purpose of this measurement is to quantify the impact of the sleeve's thermal expansion on its axial strain: is all of this expansion taken up at the insert (i.e. up to 15 mm) or only part of it (due to possible axial buckling)? It involves measuring the sleeve's mean axial strain on an inner surface and over the longest length possible (for example between sections 2 and 9). The measurement uncertainty shall be less than 20 µm/m.

3.2.3 Measurement of relative humidity in the annular space

The purpose of this measurement is to track changes in the hydric conditions in the annular space between sleeve and cell wall, in order to assess the resaturation kinetics of the near-field argillite.

The measurement of relative humidity in the annular space along the sleeve is to be performed using one measurement point per section fitted with strain gauges (see Section 3.2.1). To limit the risk of sensor damage during sleeve installation, a hermetic feedthrough device with sensor body and connector inside the sleeve is preferred.

3.2.4 Measurement of total pressure applied to the sleeve

The purpose of this measurement is to calculate the normal stress applied by the rock mass onto the sleeve's external surface. This measurement also helps determine the time required for the rock mass to converge onto the sleeve.

Each section fitted with strain gauges (see Section 3.2.1) is to be fitted with sensors for measuring the total pressure (direct measurement or via measuring load) at the sleeve/rock interface on at least two points located at approximately 45° from the horizontal diameter (see Figure 18). The measurement range of the sensors is to be at least 0 to 20 MPa. Again, a hermetic feedthrough device is preferred.

3.2.5 Measurement of temperature profiles along the sleeve

Two temperature profiles of the internal surface of the sleeve are to be produced: one along the crown and the other along a lateral generatrix (in the cell's horizontal plane). The spatial resolution of these measurements is to be no more than 2 metres (i.e. at least one measurement point per section for each profile). The measurement uncertainty is to be less than 0.5°C for a measurement range of at least 20°C - 150°C.

3.2.6 Sleeve/rock-mass clearance reduction

The purpose of this measurement is to calculate the clearance reduction kinetics in the annular space between cell wall and sleeve.

Each section fitted with strain gauges (see Section 3.2.1) is to be fitted with sensors for measuring the distance between the external surface of the sleeve and the cell wall in three directions: two horizontal and one vertical (Figure 18). The measurement uncertainty is to be less than 0.1 mm for a measurement range of at least 40 mm. Due to the significant overprofiles (breakouts) that can be generated during drilling (see Section 2.1), a difficulty for this type of measurement lies in being sure that the sensors can make contact with the rock. The technology used for measuring clearance reduction in the vertical direction must allow for a possible 100 mm overprofile. Again, a hermetic feedthrough device is preferred.

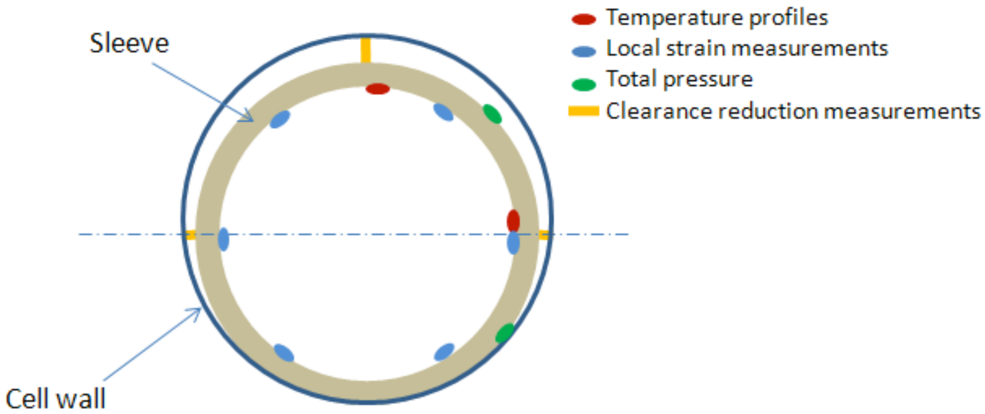

Figure 18 Summary of the measurements to be made on each of the three sections of the useful part that are fitted with instrumentation – sensors may be placed on different parts if they measure different values – the relative humidity sensor and the mean axial strain measurement device are not shown

3.2.7 Constraints shared by all useful-part sleeve instrumentation

3.2.7.1 Outline dimensions

For instrumentation on the sleeve intrados (inside wall), account must be taken of the outline dimensions associated with the presence and removal of the drilling machine and the cuttings-removal pipes. Also, the sleeve is to be fitted with a heating element whose design shall include instrumentation constraints (see Section 3.1). The heating element is to be placed on the sleeve's invert, on runners to prevent direct contact with the sleeve (see Figure 16).

With regard to the sleeve's extrados, through-wall sensors (those for relative humidity, total pressure and annular space clearance reduction) must not project from the outer surface when the sleeve sections are being installed.

3.2.7.2 Leaktightness

As for the heating element, due to the probable arrival of water into the annular space and the inside of the sleeve, sensors and their connectors must be leaktight (except for the relative humidity sensors). As the heating element could reach 100°C, leaktightness should be ensured with respect to both liquid water and steam.

3.2.7.3 Thermal loading

All sensors, their connections and any protective coverings must operate over a temperature range of 20°C to 150°C. Any thermal compensation required should be clearly established for each type of sensor and validation tests should be performed over the range 20°C to 100°C.

3.2.7.4 Cable routing

A major difficultly resulting from the presence of the useful part's head plug is the routing of cables from sleeve and heating element instrumentation. These cables are to be routed via a conduit through the plug. This conduit must be leaktight in view of the possible later installation of the clay plug. The diameter of this conduit must be suitable for the quantity of cables to be routed from the sleeve and heater element instrumentation. This conduit shall also carry all cables from the heating device and the instrumentation through the insert-head cover plate.

Cable routing through the plug raises the problem of the responsibilities of the various operators. Indeed, sleeve instrumentation is to be installed first: the sensor cables from this instrumentation will already be in place when the heating element is installed. During heating element installation, both heating element and sleeve instrumentation cables are to be grouped into the same central conduit.

Supply of this conduit and cable grouping shall be the responsibility of the heating-element service provider. Once this conduit has been installed, the sleeve cover plate shall be installed by the cell-excavation service provider (CSM Bessac).

3.3 Instrumentation for the cell-head insert

3.3.1 Measurement of strain

The aim of this measurement is to assess the main characteristics of the rock-mass load and the impact of the thermal load on the insert. It involves measuring axial and orthoradial strain and convergence on various parts of the insert. Three sections (labelled 11, 12 and 13 in Figure 19) are to have instrumentation fitted. Each of these sections is to be fitted, on its internal surface and as near as possible to its central part (depending on accessibility), with the following:

- strain gauges placed evenly around the pipe in 6 measurement areas, two of which shall be located on the horizontal diameter (see Figure 20). These sensors (extensometers or other types of strain gauge) shall be fitted to the inner surface of the pipe and should measure axial and orthoradial strain. The measurement uncertainty should be less than 10 µm/m.
- two displacement sensors to measure the radial displacement (convergence) in the horizontal and vertical directions. The measurement uncertainty should be less than 0.1 mm.

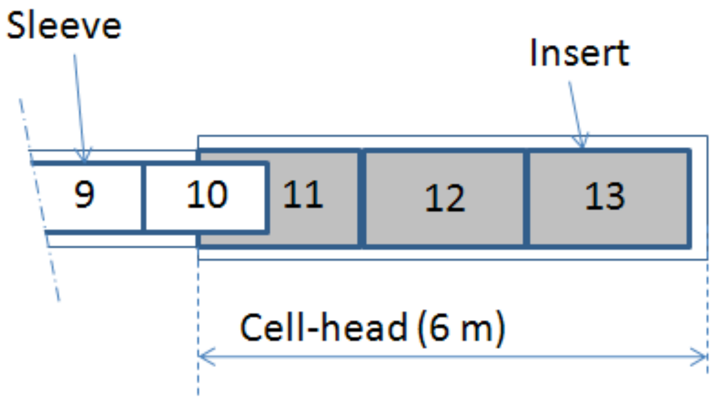

Figure 19 *Cell-head insert – the sections fitted with instrumentation are shown in grey.*

Note: during instrumentation design, the possibility of fitting instrumentation to section 9 (of the sleeve) instead of section 12 (of the insert) could be studied.

3.3.2 Measurement of relative humidity

Relative humidity measurements shall be performed along the **inside** of the insert, with one measurement point per section fitted with strain gauges (see Section 3.3.1).

3.3.3 Measurement of temperature profiles along the insert

In continuity with the measurements required in Section 3.2.5, two temperature profiles of the internal surface of the insert shall be produced: one along the crown and the other along a lateral generatrix (in the cell's horizontal plane). The spatial resolution of these measurements shall be no more than 2 metres (i.e. at least one measurement point per section for each profile). The measurement uncertainty shall be less than 0.5°C for a measurement range of at least 20°C - 150°C.

Figure 20 gives a summary of the measurements to be performed on each insert section that is fitted with instrumentation.

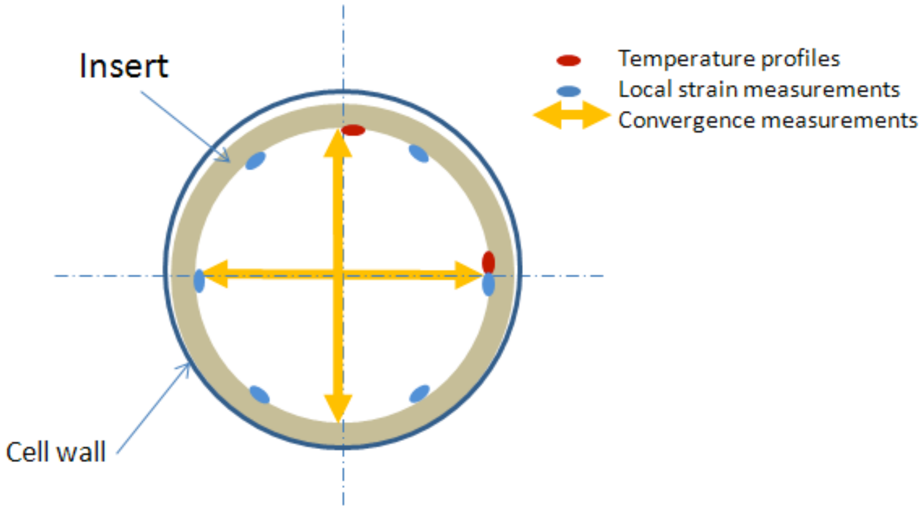

Figure 20 *Summary of the measurements to be made on each of the three sections of the insert that are fitted with instrumentation – sensors may be placed on different parts if they measure different values – the relative humidity sensor is not shown*

3.3.4 Constraints shared by all instrumentation on the cell-head insert

3.3.4.1 Outline dimensions

During the excavation phase for the cell's useful part, the whole length of the inner volume of the insert (which will have already been installed) will be occupied by sleeve sections. During this phase, the installed instrumentation must fit into a limited space (between a 700 mm diameter cylinder and a cylinder of approximately 725 mm diameter, which do not necessarily share an axis). The possible presence of sleeve centring runners should also be taken into account.

All the sensor cables should pass through the cell-head cover plate via a special conduit (see Section 3.2.7.4). Its geometry and minimum size shall be specified by the Contract Holder in consultation with the heating-element service provider.

3.3.4.2 Leaktightness

Due to probable water ingress into the annular space and the inside of the insert, sensors and their connectors must be leaktight (except for the relative humidity sensors).

3.3.4.3 Thermal loading

All sensors, their connections and any protective coverings shall operate over a temperature range of 20°C to 70°C (heating will only be applied from 4 m beyond the insert). Any thermal compensation required should be clearly established for each type of sensor and validation tests should be performed over the range 20°C to 70°C, and written up in the qualification report.

3.4 Measurement of sleeve/insert relative displacement

One of the aims of Phase 3.1 of the "HLW Cell" Programme Unit consists of ensuring that thermal expansion of the useful part is indeed taken up by sliding in the insert. The total expected expansion will not exceed 15 mm. As per the current design, the sleeve/insert junction will not be leaktight, so water may flow freely within the insert. Sleeve and insert do not have to share an axis for the experiment[3].

[3] However, the cell-excavation service provider could suggest installing rails on the insert sections to facilitate displacement of the sleeve sections and centre them; these rails would be installed after installing the insert and removing the drill and would be removed after the cell was produced. The possibility of leaving a certain length fitted with these rails, to maintain the sleeve centred in the insert during the experiment, could be studied.

The instrumentation implemented shall track the relative motion of the section marked 10 in Figure 19 with respect to the insert. The axial displacement of section 10 inside section 11 shall be measured at three points spaced at 120° (see Figure 21). On the sleeve side, the reference point for the measurement could be a point on section 10 or on its plug. If precision allows, contactless technology could be used for these measurements with a view to simplifying the instrumentation inside the insert (for example, optical measurements by a laser positioned against the head-insert cover plate). The measurement uncertainty shall be less than 0.2 mm for a measurement range of at least 20 mm.

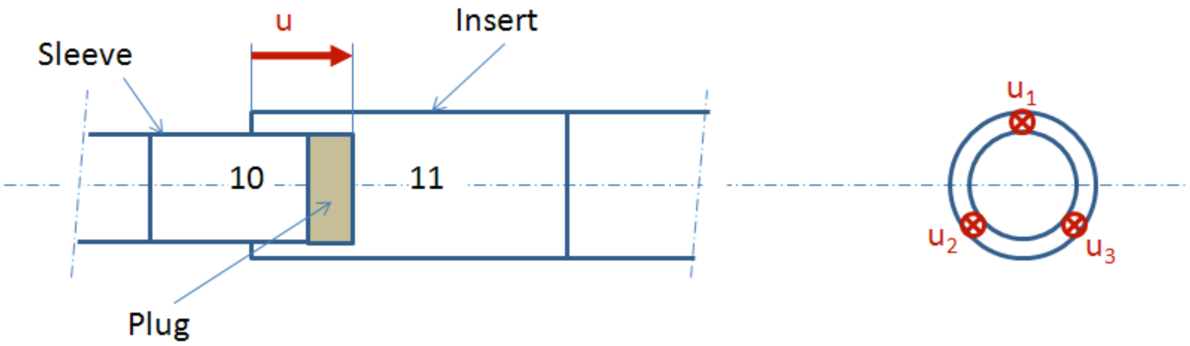

Figure 21 *Schematic diagram of the measurement of sleeve/insert axial displacement (u)*

Outline-dimensions constraint

All the sensor cables should pass through the cell-head cover plate, *via* a special conduit (see Section 3.2.7.4).

Leaktightness constraint

Due to probable water ingress into the inside of the insert, sensors and their connectors must be leaktight.

Constraint associated with thermal loading

All sensors, their connections and any protective coverings must operate over a temperature range of 20°C to 70°C. Any thermal compensation required should be clearly established for each type of sensor and validation tests should be performed over the range 20°C to 70°C, and written up in the qualification report.

3.5 Measurements associated with the THM behaviour of cell ALC1604

These measurements shall be performed in peripheral boreholes around cell ALC1604. A schematic diagram of the location of all the peripheral boreholes planned for Phase 3.1 of the "HLW cell" Programme Unit is given in Figure 15.

The boreholes (18 in total) will be drilled by COFOR (see Section 4). The precision of each borehole's trajectory is crucial. Reference points located in the drift should therefore be used to calibrate the azimuth and altitude settings of the drilling machine. At the end of drilling, the trajectory shall be measured. GEOTER shall perform a systematic structural analysis of the drill cores from the boreholes (see Section 4).

3.5.1 Experience feedback from previous thermal experiments

Previous thermal experiments performed at the *Centre de Meuse/Haute-Marne* (CMHM, Meuse/Haute-Marne Centre) – mainly the TER and TED experiments – provided important experience feedback for the design of instrumentation for the peripheral boreholes. In particular:

- Multi-packer systems for hydrogeological applications have standard (20 cm long) measuring chambers. When placed in an area subject to a large thermal gradient and orientated along this gradient, the pressure measurement may be biased by the temperature variation along the chamber. For this reason, it is preferable to use single-packer systems, characterised by shorter measuring chambers (5 cm to 7 cm);
- Classic Pt100 or Pt1000 sensors are more suitable for the temperature measurements, as duplex platinum elements can produce relatively noisy data;
- With regard to strain measurements, the very small heat-induced strain amplitudes expected implies the use of very precise measuring equipment. Experience feedback from manual micrometer measurements on boreholes, performed during previous thermal experiments, has shown the complexity of interpreting such measurements, mainly associated with difficulty in obtaining good reproducibility in the measuring procedure;
- Finally, any borehole drilled in an area under study can act as a drain. So it is necessary to limit the number of boreholes as far as possible, to minimise the hydraulic disturbance in the environment, and to use a very low permeability sealing material where equipment must be sealed in the borehole.

These lessons have been applied when specifying the characteristics of the peripheral boreholes described below.

3.5.2 Measurements of interstitial pressure

The purpose of these measurements, beyond the supplementary data they provide with respect to similar measurements performed during previous phases of the “HLW cell” Programme Unit, is to detect the overpressures generated by the thermal loading of the cell.

Classic instrumentation comprised of hydrogeology packer systems in boreholes is suggested around the planned location for producing the cell. The boreholes shall be drilled both from the GAN drift, to have measurements along the cell, and from the NRD niche, to have measurements in a plane perpendicular to the cell.

The calculations performed for a 25 m cell show that the thermal gradient is very large in the first three metres away from the cell (Figure 22). Single-packer systems must be used for the measurement points close to the cell wall from the NRD niche (Figure 15), to avoid the influence of this gradient on the measurement (see previous section). Multi-packer systems may be used for more distant measurement points.

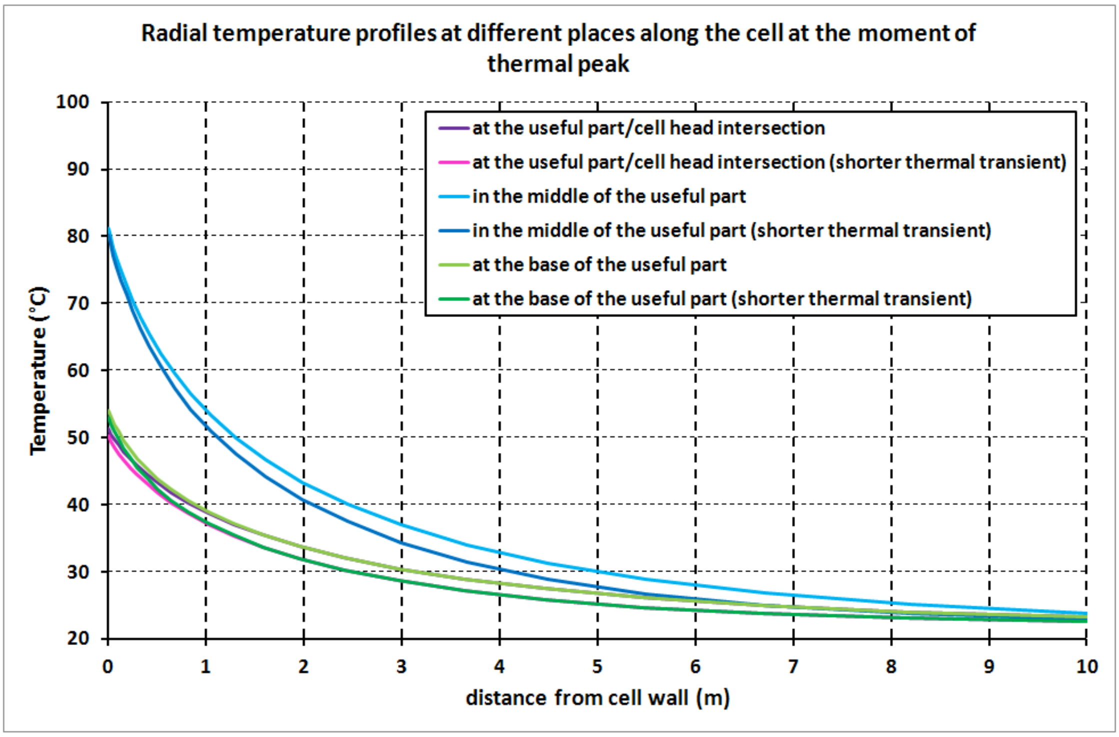

Figure 22 Temperature profile radial to the cell

Six boreholes for measurements are to be drilled:

- Three boreholes from the NRD niche, including:
  - Two boreholes (ALC4001 and 4002) fitted with single-packer systems to measure the interstitial pressure in a horizontal plane radial to the cell, at 0.75 m and 1.5 m from the cell wall respectively,
  - one borehole (ALC4005), on a rising incline and perpendicular to the cell, fitted with a multi-packer system with five measuring chambers at 4, 7, 10, 12.5 and 15 metres from the NRD niche – the 15 m chamber being located 3 to 4 metres vertically from the cell; the purpose of this borehole is to study the influence of the GAN and GRD drifts on the interstitial pressure distribution around the cell;
- three boreholes from the GAN drift:
  - one borehole (ALC1616), converging towards the cell in the horizontal plane, fitted with a multi-packer system with five measuring chambers located at 5, 10, 13, 17.5 and 22 metres from the GAN drift wall (providing a pressure profile from the GAN drift) at distances from the cell wall ranging from 1.7 to 2.4 metres;
  - one borehole (ALC1617), diverging from the cell in the vertical plane, fitted with a multi-packer system with three measuring chambers located at 13, 17.5 and 22 metres depth, corresponding to distance ranging from 2.3 to 3.6 metres from the cell wall (by making the borehole leave 50 cm above the cell with an angle of 8°); for a chamber centred at 2.3 m from the cell wall, the thermal gradient in the chamber is less than 1° (Figure 22);
  - one borehole (ALC1618), parallel to the cell at a radial distance of 50 cm, fitted with a multi-packer system with three measuring chambers (at 2, 3 and 5 metres depth), with the aim of measuring any impact of the thermal gradient along the insert on the permeability of the rock; calculations show that the thermal gradient is small in the first 5 metres of the insert from the wall (Figure 12), so the influence of the measuring chamber size will be negligible.

Table 2 summarises the borehole characteristics for measurements of interstitial pressure and permeability.

Table 2: Borehole characteristics for interstitial pressure measurements

Borehole	Location	Measurement	Type	L (m)	Ø	Slope
ALC4001	NRD niche	Interstitial pressure	1 ch. – 0.75 m from cell in the horizontal plane	13	56	Rising
ALC4002	NRD niche	Interstitial pressure	1 ch. – 1.5 m from cell in the horizontal plane	12.2	56	Falling
ALC4005	NRD niche	Interstitial pressure	5 ch. at 4, 7, 10, 12.5 and 15 metres from the NRD niche, above the cell	15	76	Rising
ALC1616	GAN drift	Interstitial pressure	5 ch. at between 1.7 and 2.4 metres from the cell in the horizontal plane (between 5 and 22 metres from the GAN drift)*	22	76	horizontal
ALC1617	GAN drift	Interstitial pressure	3 ch. at between 2.3 and 3.6 metres from the cell in a vertical plane (between 13 and 22 metres from the GAN drift)	22	76	Rising
ALC1618	GAN drift	Interstitial pressure	3 ch. at 2, 3 and 5 metres from the GAN drift	5	76	horizontal

* borehole 1.5 m from the crossing section

Pressure measurement packer systems are to be installed several months before cell excavation. For an optimum pressure recovery phase, a hydraulic test phase could be performed to promote the recovery and stabilisation of interstitial pressure.

These measurements are to be linked to the *Système d'Acquisition et de Gestion des Données* (SAGD, data acquisition and management system).

The borehole instrumentation will be installed by SOLEXPERTS (see Section 4).

For each borehole, a control panel is to be installed on the wall; its position must be carefully specified so that it is not damaged during cell excavation.

3.5.3 Temperature measurements

First of all, it should be noted that all the interstitial-pressure measuring chambers described above are fitted with temperature sensors, which already gives a good representation of the thermal field around the cell.

To supplement this network of temperature sensors, a temperature-measurement borehole (ALC4003) is to be drilled from the NRD niche in the horizontal plane radial to the cell. Calculations that have been performed show that beyond 5 m from the cell wall, the rock temperature at the thermal peak (90°C in the cell) is below 30°C (Figure 22). For this reason, this borehole shall be fitted with measuring points at 1, 2, 3, 5 and 10 metres from the cell wall.

An additional borehole (ALC1633) is to be drilled from the GAN drift, at the same radial distance from the cell as permeability borehole ALC1618, to supplement the temperature profile along the insert, with measurement points at 10, 8.5, 7, 5.5 and 4 metres depth.

These measurements are to be linked to the SAGD.

The borehole instrumentation will be installed by SOLEXPERTS (see Section 4). The sealing material shall have a permeability as close as possible to that of the rock, to limit the possibility of flow via the borehole (see previous section).

Table 3 summarises the characteristics of boreholes for temperature measurements.

Table 3: Characteristics of boreholes for temperature measurements

Borehole	Location	Measurement	Type	L (m)	Ø	Slope
ALC4003	NRD niche	temperature	5 points at 1, 2, 3, 5 and 10 metres from the cell in the horizontal plane	13	56	horizontal
ALC1633	GAN drift	temperature	5 points at 4, 5.5, 7, 8.5 and 10 metres from the GAN drift	10	56	horizontal

3.5.4 Strain measurements

The strains that the thermal loading is expected to induce around the cell are very small (Figure 23) and difficult to measure. The plan is to install a single extensometer in a borehole (ALC4004) perpendicular to the cell in the horizontal plane and ending 1 m from the cell wall. A MagX (magnet extensometer) is recommended as it has sufficient resolution (10 micron) and is temperature insensitive. These measurements are to be performed continuously (the equipment is to be connected to the SAGD), thus avoiding the reproducibility difficulties of manual measurements (see previous section).

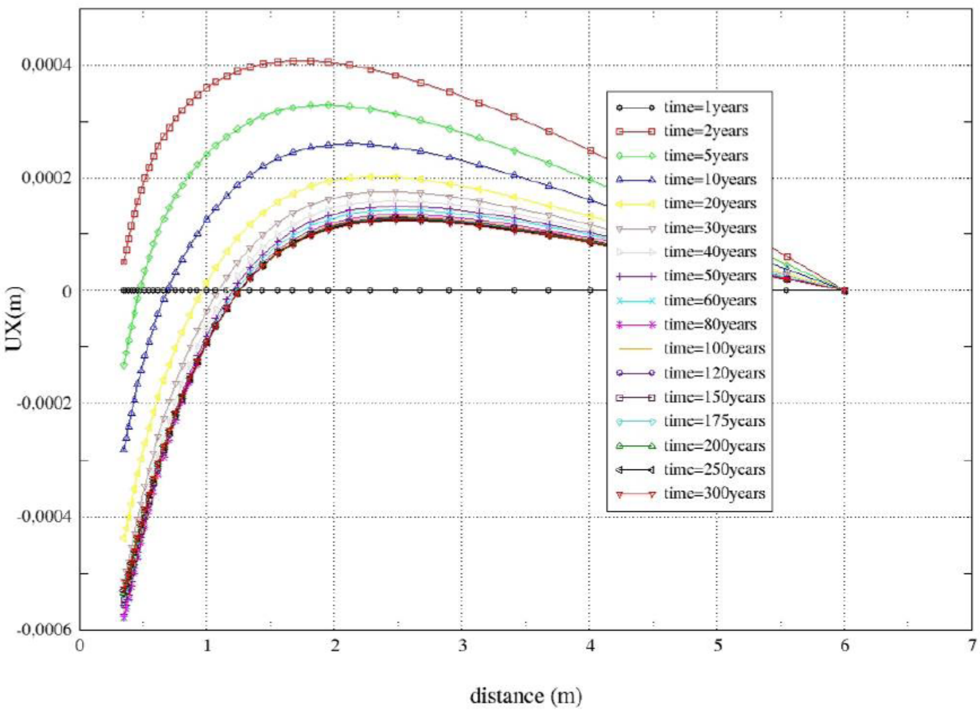

Figure 23 Radial displacement in the horizontal plane – calculation including the presence of neighbouring cells

The instrumentation for this borehole will be installed by SOLEXPERTS (see Section 4).

Table 4 summarises the characteristics of boreholes for temperature measurements.

Table 4 Strain-measurement borehole characteristics

Borehole	Location	Measurement	Type	L (m)	Ø	Slope
ALC4004	NRD niche	extensometer	20 point MagX in the horizontal plane	13	101	horizontal

3.6 Measurements of the THM impact in the GAN access drift

The impact of the heating on the access drift shall be monitored with regard to the behaviour of both rock mass and supports.

3.6.1 Rock-mass behaviour

With regard to the behaviour of the rock mass, two types of instrumentation are planned:

- one *Section de Mesures Renforcées* (SMR, enhanced measurement section) using extensometers to the right of the cell with:
    - four 30-metre-long boreholes (OHZ1605 to 1608), each with seven measurement points at 2, 3.5, 8, 11, 15 and 30 metres; of these boreholes one is to be vertical rising, one vertical falling, one horizontal to the side wall opposite the cell crossing section and one at 45° above the cell crossing section.
    - four one-metre-long boreholes (OHZ1685 to 1688), next to each 30-metre-long borehole, to give more precise information on the displacement in the first metre beyond the drift wall;

  This system allows comparison with equivalent parts installed in other drifts for the OHZ experiment.
- side-wall instrumentation in the HLW-cell crossing section, around the insert, to detect any bulging of the wall. This instrumentation is to comprise displacement sensors in contact with the wall from the cross members fixed onto the crossing section side walls. They are to be anchored into the rock at approximately 50 cm depth. A suggested installation for these measurement points is shown in Figure 24. These measurements are to be supplemented by measurements of the wall's tilt.

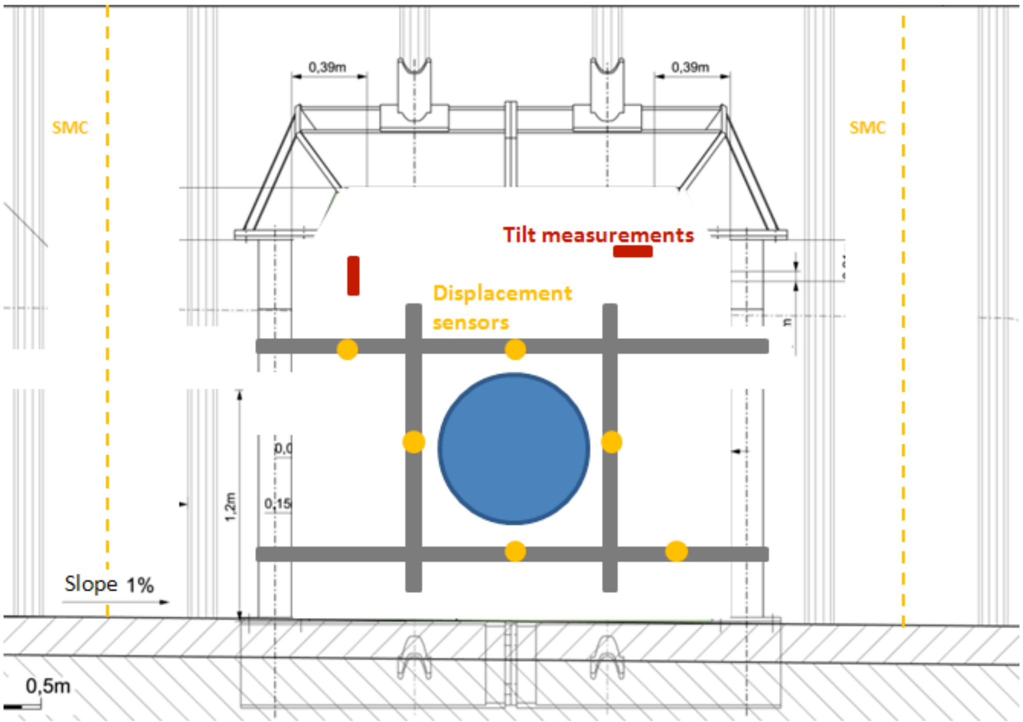

Figure 24 Suggested position of displacement and tilt measurement points for the crossing section wall – "HLW cell" Phase 3.1

Two sets of (SMC) convergence measurements are also to be installed, either side of the HLW-cell crossing section (in the neighbouring inter-arch, at 2 m either side of the cell axis).

These measurements are to be supplemented by 3D scans of the access drift at the HLW-cell crossing section (see Section 3.7.2).

The temperature and relative humidity in the drift are also to be measured at the HLW-cell crossing section.

Table 5 summarises the boreholes and instrumentation to be installed for monitoring rock mass and access drift behaviour.

Table 5: Characteristics of instrumentation for the rock mass in the GAN access drift

Borehole / sensor	Location	Measurement	Type	L (m)	Ø	Slope
OHZ1605	GAN drift	extensometer	7-point multi-rod	30	101	45° rising
OHZ1606	GAN drift	extensometer	7-point multi-rod	30	101	vertical rising
OHZ1607	GAN drift	extensometer	7-point multi-rod	30	101	horizontal
OHZ1608	GAN drift	extensometer	7-point multi-rod	30	101	vertical falling
OHZ1685	GAN drift	extensometer	single point	2	76	45° rising
OHZ1686	GAN drift	extensometer	single point	2	76	vertical rising
OHZ1687	GAN drift	extensometer	single point	2	76	horizontal
OHZ1688	GAN drift	extensometer	single point	2	76	vertical falling
ALC1641 to 1646	GAN drift	displacement	potentiometer	0.5	/	horizontal
ALC1647 to 1648	GAN drift	tilt	inclinometer	wall	/	/
OHZ1691	GAN drift	humidity / temperature		wall	/	/
OHZ160E and F	GAN drift	SMC	Distance meter	wall	/	/

3.6.2 Support behaviour

With regard to the behaviour of the supports, it is suggested that strain gauges are installed on the cell-crossing section members. These gauges are to be attached to the crossing section several months before heating starts (before cell excavation if possible, if the risk of sensor damage during machine operations can be avoided, which would also allow the impact of cell excavation to be measured), as shown in the suggested layout in Figure 25, to detect any loading of the supports due to cell thermal loading.

It is also suggested that gauges are installed on the arches, both on the two arches that lean on the crossing section and also on two more distant ones, so that any effect of the thermal field can be compared as a function of distance from the cell.

GAN drift arches are sliding arches (threshold sliding), at both the side-wall/roof and side-wall/floor junctions. To supplement the strain gauge measurements, it would seem prudent, to fit the upper (side-wall/roof) junctions of the arches that are fitted with instrumentation with displacement sensors to measure the sliding.

Table 6 summarises the instrumentation installed on the support members in the access drift.

Table 6: Characteristics of instrumentation for the ground support in the GAN access drift

Sensor	Location	Measurement	Type	L (m)	Ø	Slope
ALC1651 to 1658	GAN drift	strain	gauges	/	/	/
ALC1661	GAN drift	displacement	potentiometers	/	/	/

to 1668						

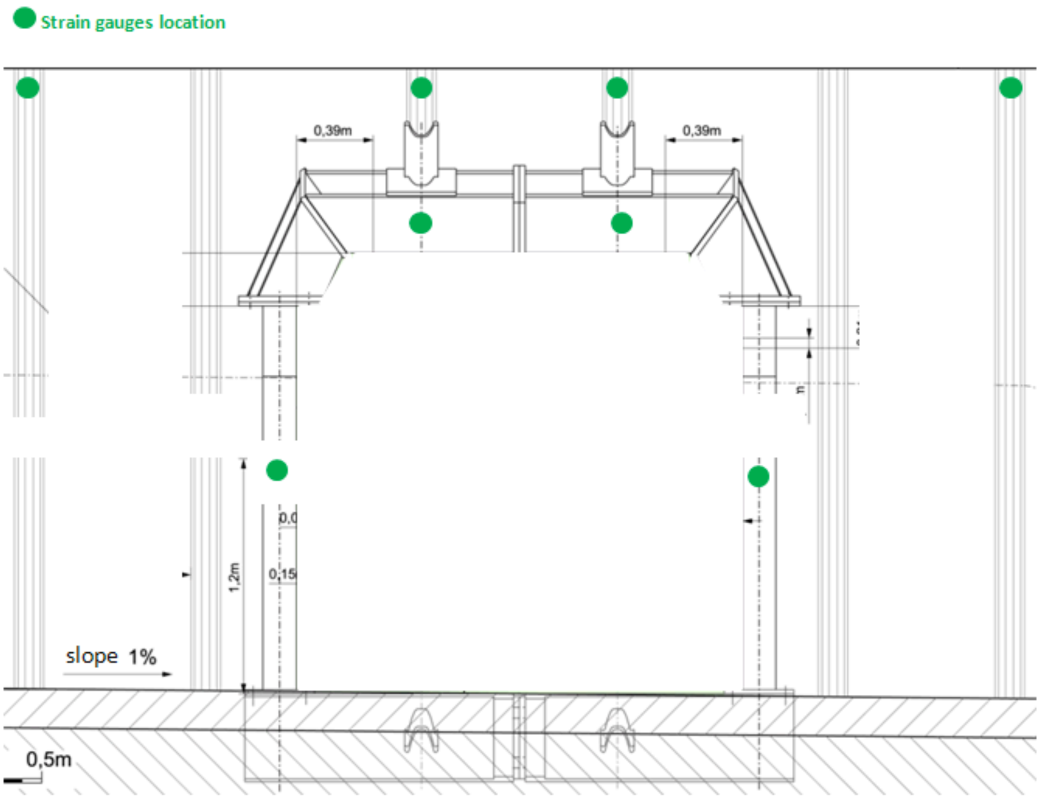

Figure 25 *Locations of strain measurements on the supports.*

3.7 Measurements associated with HLW-cell excavation

3.7.1 Measurement of excavation parameters

During cell-excavation by CSM BESSAC, several parameters are to be measured in order to understand the quality of the excavation and the performance of the machine.

These parameters are:

- instant torque on the screw,
- total instant thrust load (casing + drill head),
- excavation speed,
- rotational speed,
- working face position,
- time,
- air flowrate and injection pressure,
- daily cuttings volume,
- horizontal and vertical deviation (with a precision of 1°),
- load on the guide runners,
- temperature at the cutting head.

This data is to be acquired and supplied by CSM BESSAC (as Excel files).

3.7.2 3D scan of the cell

Two types of 3D scan are to be performed during Phase 3.1 of the “HLW cell” Programme Unit.

- 3D scan of the cell after excavation, to detect any alignment faults on the useful part's sleeve and the insert. Performance of this measurement is dependent on accessibility for the measurement system inside the sleeve, before or after instrumentation is fitted;
- a 3D scan of the GAN drift by the cell, which will be repeated at intervals during the experiment:
    - after cell excavation and installation of sleeve and insert instrumentation,
    - after installation of the heating element and closure of the cell insert head,
    - at the end of the heating phase,
    - at the end of the experiment (temperature returned to 22°C).

The purpose of the measurements is to track any strain on the GAN access drift that is caused by the cell's thermal loading.

If they are possible, these measurements shall be performed by the Contract Holder for the "3D scan" Work Package (see Section 4).

3.8 Additional measurements

3.8.1 Measurements in the cell

Changes in the useful-part/insert overlap area, in particular water or argillite ingress, is important to monitor in order to have qualitative data on this water/gas exchange zone between the cell head and the useful part. Intermittent observations of this area are to be performed (by introducing a camera, whether endoscopic or not).

3.8.2 Measurements outside the cell

A calcimetry profile is to be performed at the cell crossing section, to detect any specific geological layers that could influence cell excavation and their behaviour in retrospect.

This profiling will be performed by GEOTER (see Section 4).

4. Organisational structure for service provision

The laboratory's "experiment coordination and strategy" department (DRD/CSE) acts as both Project Owner and Lead Contractor for experiments performed in the drifts and on ground level.

Each experiment is performed under the scientific responsibility of an "Experiment Manager" from the DRD department involved.

Performance of the services required for the experiment programme, which are divided into Work Packages whose technical scope generally involves several experiments, is under the responsibility of the Work-Package Managers of the various DRD departments involved.

The HLW-cell excavation contract is under the responsibility of the laboratory's Technical Department. Instrumentation, measurement and oversight contracts are under the responsibility of the DRD (its R&D division).

The list of Work Packages, Contract Holders and Work-Package Managers is given in Table 7.

Table 7 Contract Holders and Work-Package Managers

Work Package	Title	Service Provider	ANDRA Manager
/	**HLW-cell excavation**	CSM BESSAC	L. Richard-Panot
D08/D48	Maintenance and operation of scientific equipment	SOLDATA	P. Tabani
D47	Supervision of science work	XXX	J. Le Puth
/	Analysis of THM behaviour	XXX	XXX
F16	Drilling and trajectory measurements – new drifts	COFOR	H. Rebours
G04	Geological monitoring	GEOTER	C. Righini
I23	Hydrogeological instrumentation	SOLEXPERTS	M. Cruchaudet
I57	Instrumentation for sleeve and insert	EGIS Géotechnique	F. Bumbieler
I58	Heating element supply and installation		N. Conil
I60	Geotechnical instrumentation	SOLEXPERTS	J. Zghondi
M36/Mxx	3D scanner	BRISSET PERAZIO/XXX	N. Conil/J. Le Puth

5. Forecast schedule and phasing of operations

Production of the cell and the associated measurements and instrumentation may take place at the same time as other experiments in other drifts in the laboratory. The general schedule for experiments and demonstration tests is dependent on the number of places available for staff. Shift work (on the site's 3x8h basis) is encouraged.

Thirteen boreholes are planned for the GAN drift (8 SMR boreholes plus 3 for interstitial pressure, 1 for temperature measurement and 1 for fibre-optics) and 5 for the NRD niche (3 for interstitial pressure, 1 for temperature and 1 for stress measurements). These 18 boreholes are to be drilled before the ALC1604 cell is excavated: at minimum, the boreholes from the NRD niche and the long boreholes for pressure-measurement (ALC1616 and ALC1617) are to be drilled, while the other boreholes – for permeability (ALC1618), temperature (ALC1633) and fibre optics (ALC1634) – could be drilled later depending on the GAN drift excavation schedule.

At the time of writing, it is planned that these boreholes are drilled in October 2011. Measurement boreholes are to be fitted with instrumentation immediately. The pressure-measurement chambers must then be artificially filled with water and brought to equilibrium. This equilibrium requires at least 6 weeks for the pressures to stabilise.

Excavation of cell ALC1604 is planned for May 2012. The installation of sleeve instrumentation (for both insert and useful part) will be performed at that time. The (first) 3D scan of the cell and the part of the GAN drift adjacent to the cell is also to be performed at that time.

If possible, instrumentation is to be installed on support members (crossing section and arches) before cell excavation. Instrumentation is to be installed on the cell crossing section (for measurements of wall bulging around the insert, as displacement and tilt) after cell excavation to avoid damage during excavation work.

It will be necessary to wait for pressures to stabilise before the heating element can be installed and heating started (heating element installation will require the removal and replacement of the convergence sensors in the insert). This period could also see renewed drilling in the GAN drift. In this case, the heating element may be installed and heating started several months after excavation. The useful-part head plug and the insert-head cover plate are to be installed at that point.

The master schedule for Phase 3.1 of the "HLW cell" Programme Unit, which is subject to change depending on the general schedule for drift excavation, is given in Figure 26.

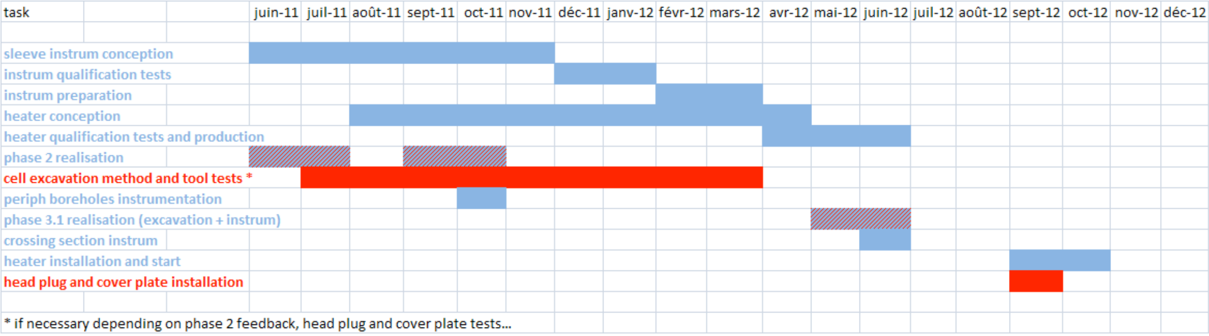

Figure 26 Master schedule for Phase 3.1 of the "HLW cell" Programme Unit

PART II – RISK ANALYSIS

1. Risk analysis

1.1 Technological and scientific risks

1.1.1 Cell production

A 740-mm-diameter cell fitted with a 700-mm-external-diameter sleeve has already been produced during previous phases of the Programme Unit. However, for Phase 3.1, the “useful part” of the cell will be excavated from within the insert, which has never been done before. This operation could, therefore, present technological risks. The risk must be minimised by optimising the diameter and thickness of the insert to allow sufficient insert/useful-part clearance.

The insert test performed in June 2011 as part of Phase 2 showed that risks also exist during cell-head excavation and insert installation. These risks shall be minimised by modifying the characteristics of the cell head and insert (length limited to 6 m, annular clearance increased to 10 to 12 mm, see Section 2.4.1.1).

1.1.2 Cell equipment

The cell equipment, whether its constituent parts (base plate, sleeve head plug, insert-head cover plate) or its instrumentation, presents significant risks related to the validation of the installation procedures that involve staff operations inside the cell. The installation procedures will be tested “on-site” as part of Phase 2 of the "HLW cell" Programme Unit (a ground-level test was validated in May 2011).

If the installation procedures planned for Phase 2 of the “HLW cell” Programme Unit are validated, experience feedback from Phase 2 (planned for October 2011) will help optimising these installation procedures for Phase 3.1. However, for Phase 3.1, the later installation of the heating system and sleeve head plug will require all instrumentation and heating system cables to be grouped into a central conduit up to the head-insert cover plate. This operation will involve significant interaction between various service providers involved (those responsible for sleeve instrumentation, the heating system and plug installation) which must be carefully planned, in particular by performing joint tests at ground level.

In the event of the installation procedures planned for Phase 2 encountering difficulties, it will be necessary to specify new installation procedures for the cell, which could lead to modifications to either the drilling machine (cutting wheel and guide runner configuration), the sleeve (machining for instrumentation) or the instrumentation (issues concerning cable routing and the size of certain sensors). In addition, the installation procedures for the plates (base plate and sleeve-head plug) may also need to be modified.

1.1.3 Scientific risks

At the time of writing, the characteristics of the (sleeve and heating system) instrumentation, which are to be installed in Phase 3.1 of the "HLW cell" Programme Unit, are not yet known. However, the technology used should be largely similar to that generally used in the laboratory (strain gauges, potentiometers or linear variable differential transformers (LVDTs), platinum thermocouples, 4-20 mA sensors for the instrumentation and resistors or heating cables for the heating system). Although arriving late in the day for Phase 3.1 sleeve instrumentation design, experience feedback from the installation of the sleeve fitted with instrumentation in Phase 2, planned for October 2011, could allow certain points to be optimised.

As for the previous “HLW cell” Programme Unit, instrumentation shall be installed in the peripheral boreholes around the cell before the cell is excavated (interstitial pressure and strain measurements). Cell trajectory must, therefore, be carefully managed.

One unknown concerns the possible risk of the formation of an explosive atmosphere in the cell, after closure of the sleeve-head plug and insert-head cover plate, due to the production of hydrogen by anoxic corrosion of the sleeve. Experimental data on the production of hydrogen in a sleeved cell (ALC3004), performed in Phase 1 of the "HLW cell" Programme Unit, may be available from the end of 2011. The risk must be managed by modifying the plug and cover plate to allow measurement and treatment of the internal atmosphere before operations in the insert such as for intermittent observations (see Section 2.4.1.6)

1.2 Risks associated with scheduling

Phase 2 experience feedback shows that machining operations on the sleeve sections constitutes a critical task that requires significant planning.

The risks regarding scheduling are mainly associated with the validation or otherwise of the installation procedures for cell equipment. If difficulties are encountered, the modifications required on the drilling equipment, sleeve or instrumentation could produce additional delays for Phase 3.1.

In contrast, the schedule for tasks relating to supply of the heating system (Work Package I58) is less tight.