WORKPACKAGE - FINAL REPORT

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LUCOEX

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Final Report LUCOEX – WP3

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Summary

The main aims of ALC full scale emplacement experiment performed within the context of WP3 were to demonstrate the construction feasibility of a High Level Waste (HLW) cell representative of the 2009 benchmark 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. All the objectives were achieved.

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%, 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 off had no impact on the overall THM behaviour of the cell.

The hydromechanical 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 tubings 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 overpressures 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 quite 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 permitted 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.

Contents

1 LUCOEX WP3 : ALC full scale emplacement experiment

1.1 Context and Objectives

1.1.1 2009 HLW cell concept

According to Andra's 2009 benchmark concept, the HLW cell (Figure 1) 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 natural mechanical stress field. 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.

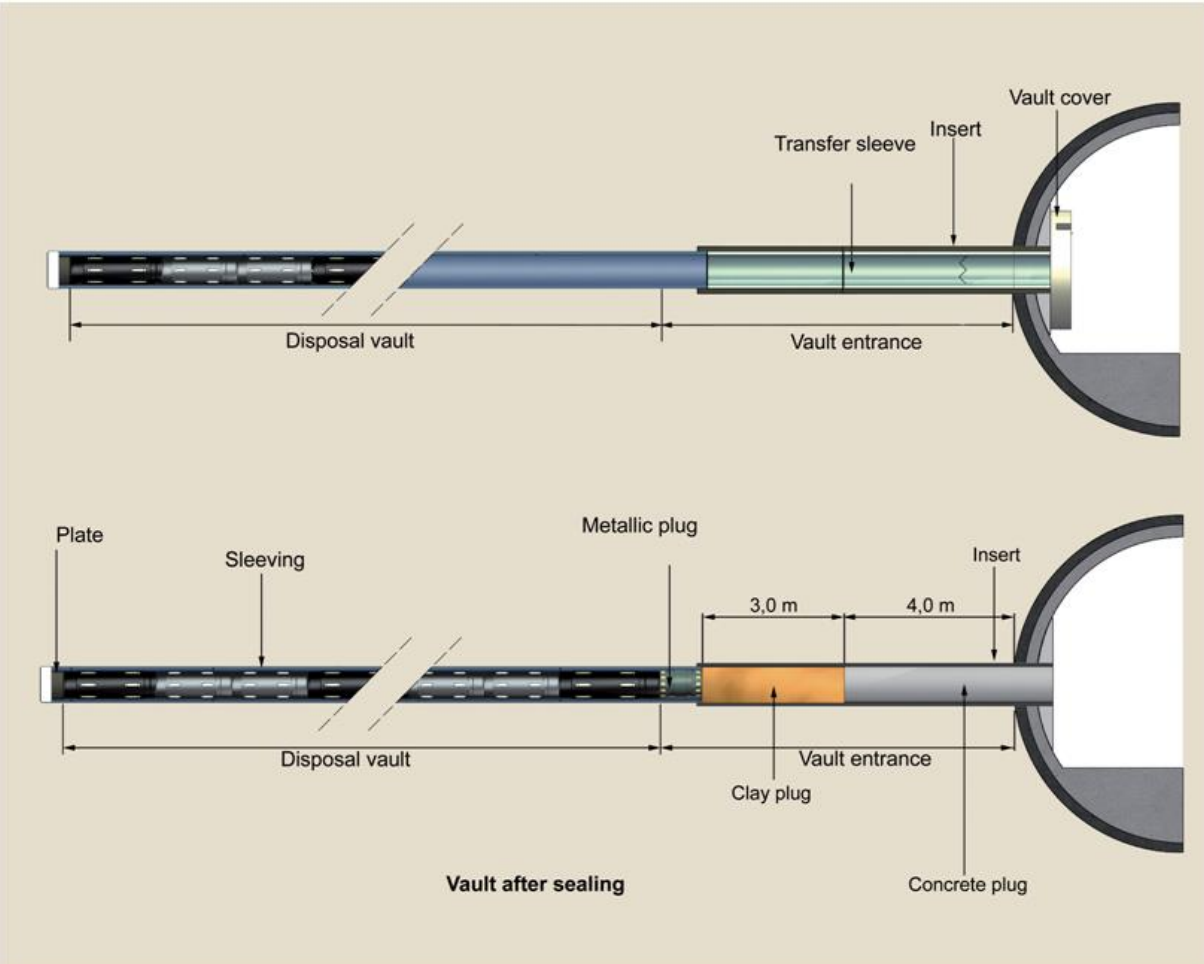


Figure 1 Schematic diagram of a HLW cell according to 2009 benchmark concept

The sleeve thickness (25 mm) has been calculated to prevent against rock deformation and allow the potential retrieval of waste containers during the reversibility period. The cell-head insert has also been designed to allow reversible operation of the 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.

1.1.2 Purpose of the “HLW cell” Programme Unit

The “HLW cell” Programme Unit performed in Andra’s Underground Research Laboratory (URL), 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 Callovo-Oxfordian (Cox) claystone 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.

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.

1.1.3 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 “H0” 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 Cox claystone 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” claystone in association with the THM behaviour of the rock/sleeve interface.

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.

1.2 Scientific and Technical Results

1.2.1 Cell characteristics and instrumentation

A general view of the experiment is shown in Figure 2.

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 an overlap zone 1 m in width 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;
- 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, but the simulations performed for the design have shown that a heating length of 15 m is sufficiently representative to provide an understanding of the behaviour of both the cell and the surrounding rock) meet the requirements for proving the 2009 concept.

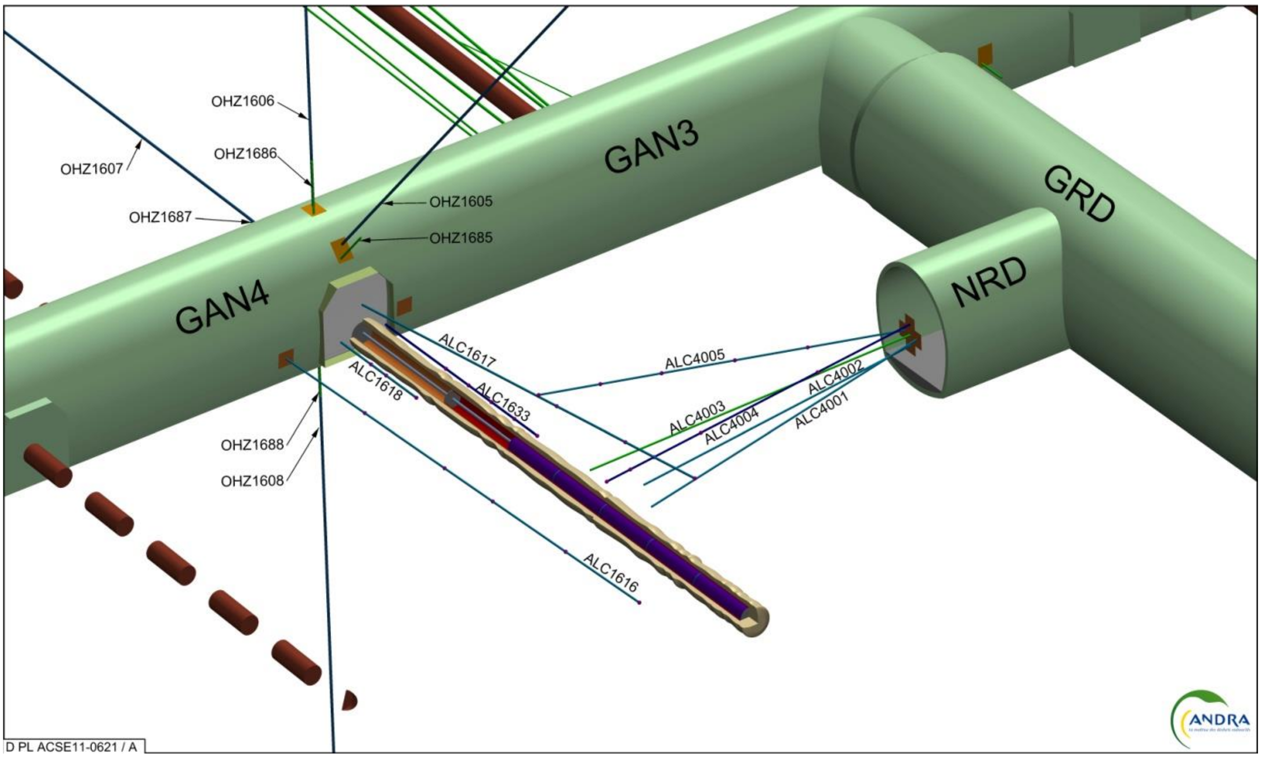


Figure 2 General view of the "heated cell" experiment

Figure 3 shows the location of the sleeve sections and insert sections equipped with sensors in the cell.

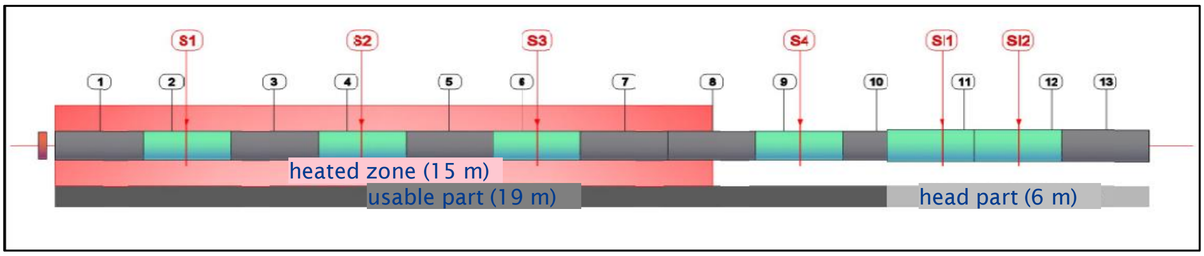


Figure 3 Location of the sleeve sections and insert sections equipped with sensors

Each sleeve section equipped with sensors contains the following (Figure 3):

- six strain gauge sectors at the sleeve intrados, with an axial gauge and a circumferential gauge for each sector; these sectors are positioned horizontally and at a 45° angle; unlike the gauges installed on the CAC1601 cell sleeve in Phase 2, these are stuck directly onto the steel at the bottom of counterbores 7 mm in depth, and not onto steel foils;
- three rock/sleeve clearance measurement sensor sectors, one at each side and one in the vault; the principle of the sensor consists in placing a piano string into contact with the rock with an angle gear on a displacement detector fixed to the sleeve intrados; unlike the other sensors in contact with the annular space, the space (10 cm in diameter) for the sensor is not filled (Figure 4);
- a relative humidity/temperature sensor taking a measurement in the annular space 15° below the horizontal axis;
- For section 9 (Figure 3), two convergence sensors for measuring the horizontal and vertical convergence of the sleeve.

In addition to these sections equipped with sensors, two temperature profiles are measured (one measurement point per section, 15° from the vertical axis and 15° above the horizontal axis).

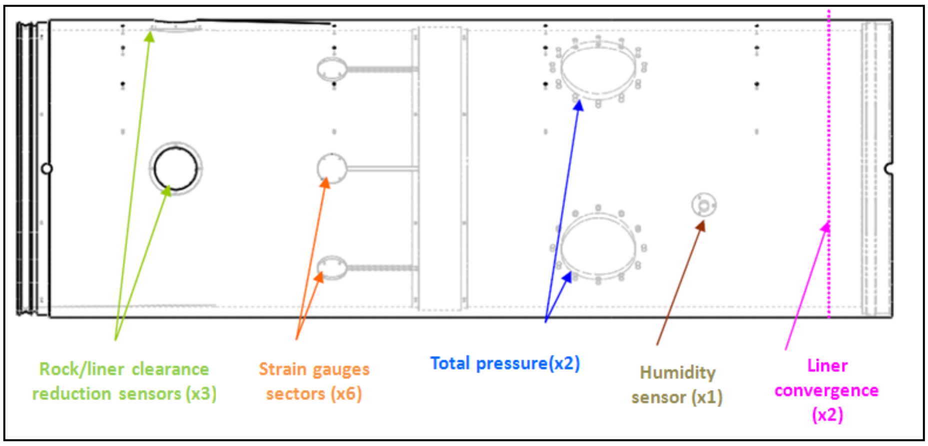


Figure 4 Location of the sensors on the sleeve sections equipped with instruments

The two insert sections equipped with sensors each contain the following:

- six strain gauge sectors on the sleeve intrados, with an axial gauge and an circumferential gauge for each sector in the same configuration as the sleeve sections equipped with sensors;
- a relative humidity/temperature sensor taking a measurement in the insert 15° below the horizontal axis;
- two convergence sensors for measuring the horizontal and vertical convergence of the insert.

Lastly, three displacement sensors fixed to the insert intrados and resting on the useful part's head plate measure the relative displacement of the sleeve in the insert.

The instruments peripheral to the cell include nine boreholes drilled from the GAN access drift and the NRD perpendicular drift to monitor the temperature, the pore pressure and the deformation of the surrounding rock, as well as instruments in the GAN access drift (instruments at the cell intersection, in the arches at either side of the intersection, and sensors measuring the temperature and relative humidity in the drifts).

1.2.2 Cell excavation

The excavation of the cell began on 23 October 2012.

The cell head was excavated from 23 October at 11am to 24 October at 3am, thus taking 16 hours to cover a length of 6 metres (just over 5.5 metres in the ground, equal to 0.35 metres per hour).

The configurations of the drilling machine and the drilling bench were then modified to take account of the change in the diameter of the borehole and the liners (the rock mass had been excavated some tens of centimetres beyond the insert to allow for the deployment of eccentrics 750 mm in diameter). Guide rails were also installed in the inserts so that the liners and the inserts would be concentric. These operations took 11 hours.

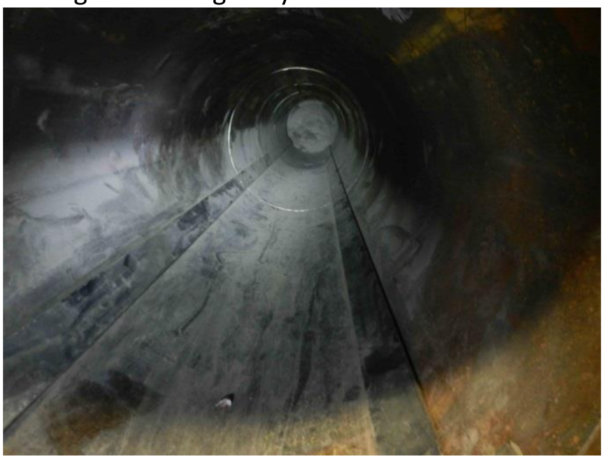
The useful section of the cell was excavated in two phases:

- an initial phase from 24 October at 2pm to 26 October at 6am, with excavation up to metric point 24.3, equal to just over 18 meters in 40 hours (0.46 meters per hour); the thrust remained low, even though an increasing rise in pressure was observed on the liners; at 70 cm from the target depth (25 meters), the eccentrics became blocked in the liner at the head, causing the coupling between the conical screw and auger no. 1 to break; as the drill head could not then be pulled out with the drill string, a system of metal chains, requiring intervention by personnel inside the cell, had to be used to release and retrieve it;
- after the machine was repaired, further work by personnel inside the cell, to perforate the face with a pneumatic drill and clear the space required to deploy the eccentrics, failed to allow the drilling work to resume (due to insufficient space between the face and the liner at the head); it was therefore decided to excavate the last few dozen meters by reverse rotation, with a diameter of 600 mm, and then to push the liner sleeve; this procedure was used to excavate an additional 50 cm on 31 October, reaching a depth of around 24.8 meters.

Figure 5 presents several photographs showing different phases of cell excavation.

Drilling station in gallery

Drill head in position



View of the inserts with guide rails

Fixation of the insert at the cell head

Figure 5 Cell excavation

1.2.3 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 six transfer skids constructed in highly resistant plastic embedded in metal parts that are themselves welded to the heat source (Figure 6). 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 6 *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.

With the exception of a few occasional adjustments, the second year of heating was characterised by four faults in four separate heater elements:

- heater element no. 4 from 11:00 AM on 8 March 2014 to 5:30 PM on 10 March, i.e. **54.5 hours**;
- heater element no. 1 from 2:00 AM on 4 June 2014 to 5:00 PM on 5 June, i.e. **39 hours**;
- heater element no. 3 from midday on 6 November 2014 to 2:30 PM on 7 November, i.e. **26.5 hours**;
- heater element no. 2 from 11:30 PM on 26 December 2014 to 10:00 AM on 5 January 2015, i.e. **226 hours**.

The impact of these successive faults, which were caused by the control cabinet fans failing, was reduced by the fact that the other four heater elements functioned normally. The overall evolution of the sleeve temperature was therefore little affected and reached a maximum of 85°C at the centre of the heated zone after two years. Locally, however, the temperature dropped considerably by between 8 and 15° at the sleeve intrados depending on the length of the fault (Figure 7 on the left). As it can be seen on Figure 7 on the right, the temperature profile on the side of the sleeve remains still approximately 4°C lower than that measured in the vault after 2 years of heating. This difference can be explained both by convection occurring inside the sleeve (hot air rises) and by the influence of the boundary conditions around the sleeve (the contact between the sleeve periphery and the rock is not homogeneous and is greater in the horizontal direction, as the direction of the loading shows). In both cases, the highest temperature is located at a depth of approximately 18 m, in other words, at the centre of the heated zone between 10 and 25 m.

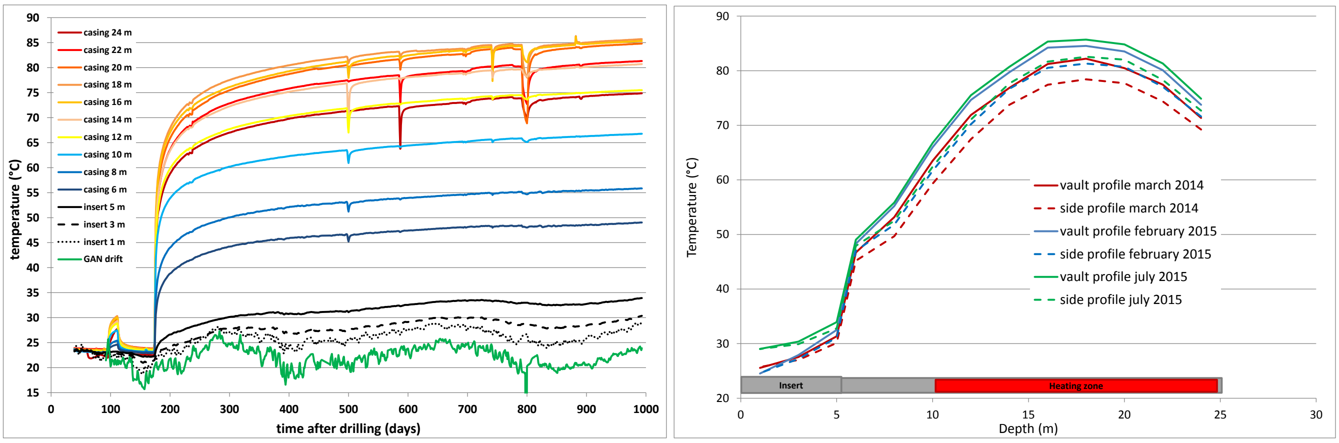


Figure 7 *Temperature evolution in the vault of the sleeve (left) and axial thermal profile in the vault and on the side of the sleeve at various dates (right)*

1.2.4 THM impact on the surrounding rock

The hydro-mechanical impact of the cell excavation, monitored on the peripheral boreholes, is consistent with the measurements taken during the excavation of the previous cells parallel to the major horizontal stress. Indeed, the excavation leads to pore pressure increase in the horizontal plane of the cell and to pore pressure drops in the vertical plane (cf. Figure 8).

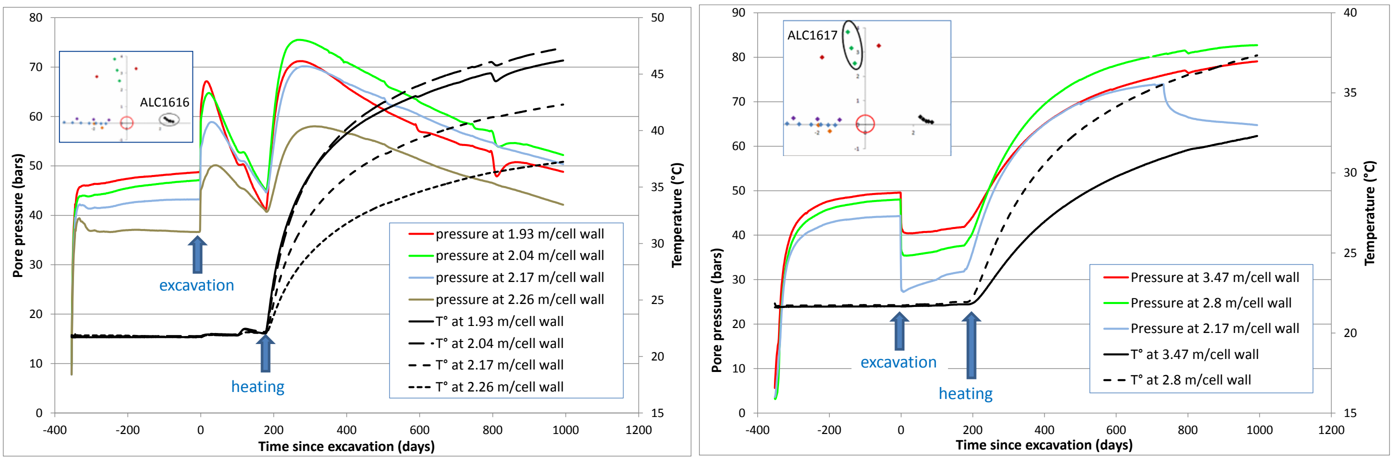


Figure 8 *Pore pressure and temperature evolution in the ALC1616 borehole in the horizontal plane of the cell (left) and in the ALC1617 borehole in the vertical plane of the cell (right)*

As was seen in the TED experiment [1], the influence of heating upon the pore pressure firstly results in thermal pressurisation (linked with the difference between the thermal expansion coefficients of the pore water and of the rock), followed by the dissipation of the overpressure when the speed of the temperature rise decreases (Figure 8). Although the overpressure peak was observed in the cell's horizontal plane in the 140 days after heating began for the measurement points located between 1.09 and 2.26 m from the cell wall, this peak had not yet been reached in the vertical plane above the cell (the closest point was 2.17 m away) after more than 800 days. The difference between the times taken to reach the overpressure peak in the vertical and horizontal planes can be explained by the anisotropic thermal and hydraulic properties of the rock.

The thermal pressurisation coefficient, which is calculated as the slope of the linear part of the ΔP/ΔT curve when heating began, was between 3 and 5 bar/°C, which is consistent with the value calculated for the TED experiment.

The considerable pressure drop measured 730 days after drilling in the chamber at 2.17 m from the cell wall (blue curve, Figure 8 on the right), which has tended to stabilise since then may be due to a sealing failure in the packers insulating the chamber.

1.2.5 Evolution of the cell measurements

1.2.5.1. Hydric conditions in the cell

The relative humidity/temperature sensors on the sleeve sections measure the relative humidity and the temperature in the annular space between the rock and the sleeve; the sensors on the inserts measure the relative humidity and the temperature in the insert.

The deepest sensor (21.5 m) was lost when heating began. The second-deepest sensor (17.5 m) ultimately also no longer functioned after recording resaturation (100%) after six months of heating (Figure 9). The other two sensors located in the annular space, at 13.5 m in the heated zone and 7.5 m outside the heated zone, seemed to have stabilised after slightly more than 2 years, at relative humidities of 86% and 70%, respectively. These measurements are the result of a balance being reached between the desiccation linked with the heating and the arrival of water linked with the rock being drained by the cell, the extent of which depends on the hydraulic gradient and therefore the depth relative to the access drift. The sensors in the insert monitor the humidity variations recorded in the GAN access drift.

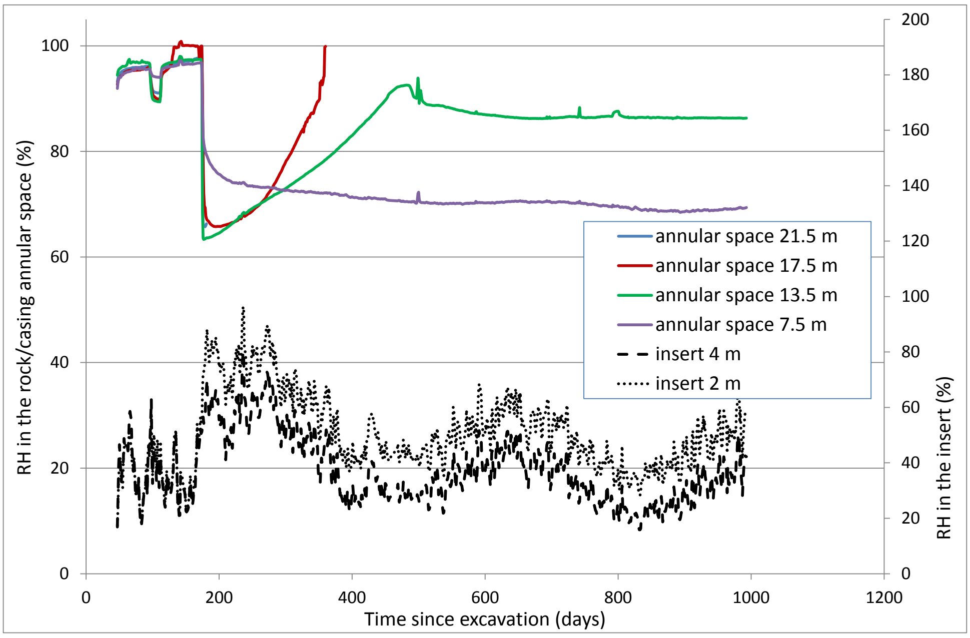


Figure 9 *Overall evolution of relative humidity in the annular space at different depths and in the insert (dashed lines) in comparison with the relative humidity in the GAN drift (blue curve at the bottom)*

1.2.5.2. Sleeve mechanical loading

Sleeve convergence

The convergence measurement sections were installed in sleeve section 9, at a depth of 7 m, and inserts 11 and 12, at respective depths of 4 and 2 m in the cell. Figure 10 shows the overall evolution of the measurements taken since the sensors were connected 48 days after the cell was excavated. As soon as the sensors were connected, it could be seen that the sleeve was loaded in the horizontal direction, resulting in it becoming oval. This behaviour is similar to that observed in the previous cells with the same orientation and is linked with the following:

- the geometry of the damaged zone around the cell, which is more pronounced horizontally and generates rock convergence mainly in the lateral plane as a result;
- the presence of excavation rubble in the annular space, which rapidly transmits the convergence from the rock to the sleeve in the lateral plane.

When heating began, the sleeve diameter variations accelerated considerably until they levelled out approximately 400 days after the cell was excavated. This levelling out tends to show that the initial annular space was fully taken up vertically by the rock convergence and the sleeve becoming oval, as was observed in the tests performed on tubing fitted with measuring instruments [2]. It can even be seen that, from this moment, the sleeve began to become less oval as a result of a decrease of the load anisotropy. In the case of the forty-metre-long CAC1601 cell fitted with instruments, only one of the four sleeve convergence measurement sections, at a depth of 35 m, ceased to become more oval between 400 and 500 days after excavation; the three other sections at depths of 7, 15 and 25 m were still becoming increasingly oval after more than 900 days, even though the initial annular space was smaller (4 cm in diameter compared with 5 cm for the heated cell). This difference may be related to the fall of spalls due to desiccation generated by heating and/or thermal additional damage of the rock around the cell.

The behaviour of the insert sections does not show any significant heating impact (the sections were 8 and 6 m behind the heated zone). On both sections, the loading schema is the reverse of that seen for the sleeve, consisting of vertical convergence and noticeably equivalent horizontal divergence. Given that the annular space is much smaller at the insert level (initially 12 mm at the radius, compared with 25 mm around the sleeve), this behaviour could be caused by the insert being in contact with the rock in the vertical and horizontal planes. As the mechanical strength of the rock was lower horizontally due to the damage generated during excavation [3], the insert tended to diverge horizontally. For both sections the loading direction is reversed relative to the sleeve, i.e. vertical convergence and noticeably equivalent horizontal divergence.

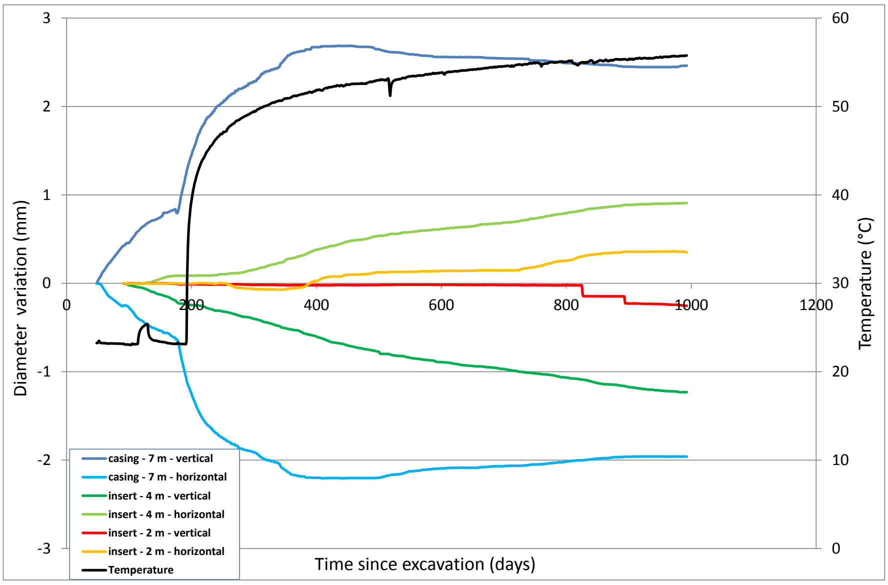


Figure 10 *Diameter variations measured on the sleeve at a depth of 7 m and on the insert at a depth of 4 and 2 m (negative values = convergence)*

Rock/Sleeve clearance evolution

The rock/sleeve clearance measurements are taken on sleeve sections 2, 4, 6 and 9 at respective depths of 22.5, 18.5, 14.5 and 8.5 m in the cell. The initial clearance was measured when sensors were installed, after the rubble jammed in the interface was cleared, and is provided for each sensor in Table 1. It can be seen that the annular clearance in the arch is theoretically less than 5 cm, implying the presence of a rubble layer on which the sleeve rests. At the side wall, on the other hand, a total left/right value exceeding the theoretical 5 cm was measured at a depth of 22.5 m, resulting from the presence of overbreaks linked with the scales.

Table 1 Sleeve/rock distances measured when the sensors were installed

Sensor no.	Value measured	Sensor no.	Value measured
Left horizontal 22.5 m	42 mm	Left horizontal 14.5 m	No measurement
Vertical 22.5 m	8 mm	Vertical 14.5 m	11.8 mm
Right horizontal 22.5 m	26 mm	Right horizontal 14.5 m	21 mm
Left horizontal 18.5 m	32 mm	Left horizontal 8.5 m	No measurement
Vertical 18.5 m	16.5 mm	Vertical 8.5 m	21.3 mm
Right horizontal 18.5 m	12 mm	Right horizontal 8.5 m	29 mm

Figure 11 shows the evolution of the measurements taken since the sensors were connected on 24 November 2012 for the sections at depths of 22.5 and 18.5 m and on 5 December 2012 for the sections at 14.5 and 8.5 m, i.e. 29 and 40 days after the cell was excavated, respectively.

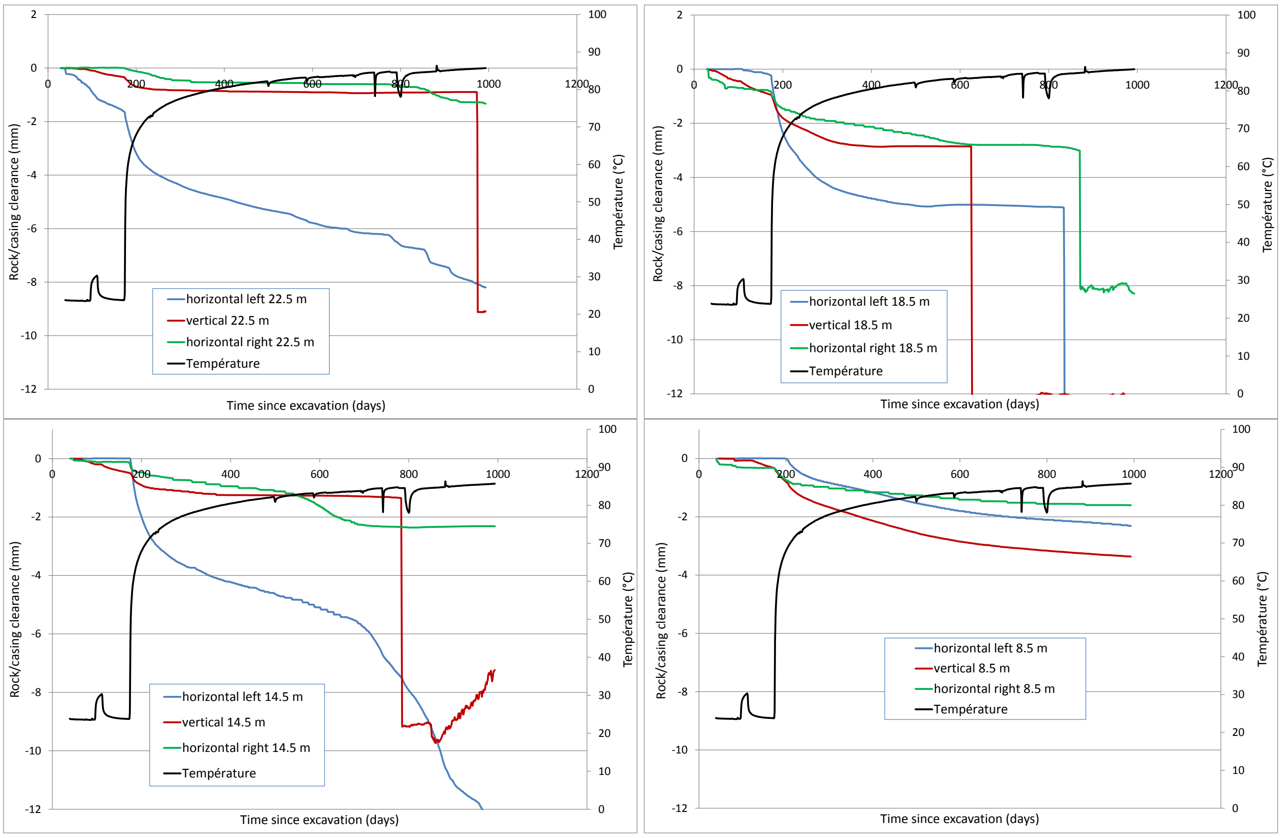


Figure 11 Evolution of rock/sleeve clearance at depths of 22.5, 18.5, 14.5 and 8.5 m (blue = left horizontal, red = vertical, green = right horizontal, black = sleeve temperature at 18 m depth)

The clearance measurements show that the clearance take-up rapidly accelerates due to heating, mainly on the left side of the sleeve, showing that the sleeve is off-centre in the cell.

The main findings are as follows:

- For the three measurement sections in the heated zone, the vault clearance, which varied between 0.9 and 2.8 mm (the maximum for the section at 18.5 m), stabilized at exactly the same time as the sleeve ceased to become more oval as detected by the diameter variation sensors at a depth of 7 m; strike-slip faults then occurred in the sections at 18.5 and 14.5 m, probably as the result of vault blocks falling (the strike-slip faults measured do not entirely take up the clearance measured when the sensors were installed). These falling may damage some sensors as it can be seen at a depth of 14.5 m.
- The wall measurements are influenced by scales breaking away from the wall, notably in the section at 14.5 m which exhibited slope changes in the left and right walls; the left and right walls of the section at 18.5 m tended to stabilize prior to a fall from the left wall, probably due to a brutal scale movement; the total horizontal clearance ranges from 7.5 mm in the section at 22.5 m to 18.4 mm in the section at 18.5 m (11.3 mm in the section at 14.5 m); the annular space at the left wall narrowed considerably more than that at the right wall because the annular space was initially wider at the left side (see Table 2), and there was potentially less rubble there.
- In both cases (in the vault and horizontally), the maximum was therefore measured for the section at a depth of 18.5 m, at the heart of the heated zone where the temperature increase was greatest; the values at 22.5 and 14.5 m were similar, like the temperature.
- Outside the heated zone at a depth of 8.5 m, the clearance values are logically smaller, greater in the vault at 3.2 mm, and with a total of 3.7 mm horizontally; these values did not stabilize, however.

Strain gauges measurements

The strain gauges, which were preinstalled on sleeves 2, 4, 6 and 9 and on inserts 11 and 12, at depths of 22, 18, 14, 8, 4.5 and 3 m in the cell, respectively, were connected on 22 November 2012, i.e. 27 days after the cell was excavated. For each section, the gauges are spread out into six sectors, two in the horizontal plane and the other four at 45° angles on either side of it, and an axial measurement and a circumferential measurement for each sector.

The axial gauges generally only show small deformations of less than 150 µm/m, and very little change over a year. Two of the 24 axial sleeve gauges appear to have malfunctioned since the beginning (virtually zero variations) and two others were lost during the second year of heating (in the section at a depth of 22 m). Only two gauges had values above 150 µm/m. This finding is not surprising and can partly be explained by the sliding of the sleeve in the insert, thereby reducing the axial constraint upon both the sleeve and the insert.

The mechanical signatures (i.e. evolution of the circumferential mechanical strain around the inner face of the sleeve) of the load applied to the sleeve at 14 and 18 m depth are presented in Figure 12. They are representative of a mainly horizontal loading of the sleeve and don't evolve significantly during the second year of heating.

The successive individual faults in the heater elements, on the other hand, were recorded for these measurements, particularly as the heater element concerned is near to the section in which the measurements were taken. This influence did not affect the overall evolution of the measurements.

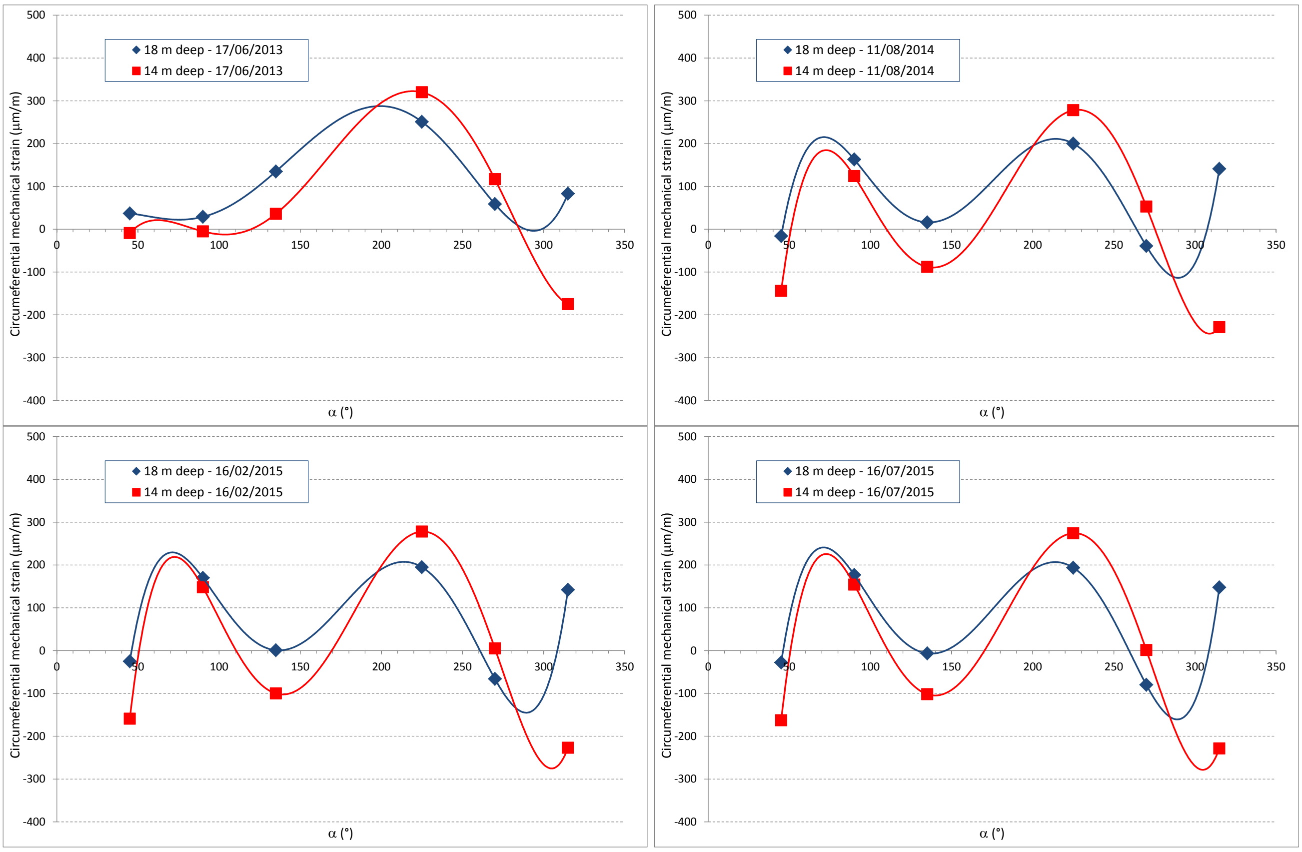


Figure 12 *Evolution of the mechanical signature of the loading at 14 (in red) and 18 m (in blue)*

The section at a depth of 8 m, outside the heated zone, also changed little, with deformations that were still low (less than 150 µm/m) and do not exhibit any well-defined mechanical signatures.

1.2.5.3. Sleeve sliding in the insert

The sliding of the sleeve in the insert vary between 2.6 and 2.7 mm in the lower part of the sleeve, where they stabilised, and 4.2 mm in the arch where slight changes could still be seen (Figure 13). This difference could partly be due to the 4°C measured difference between the arch and the sleeve wall and to an axial bending of sleeve element n°10.

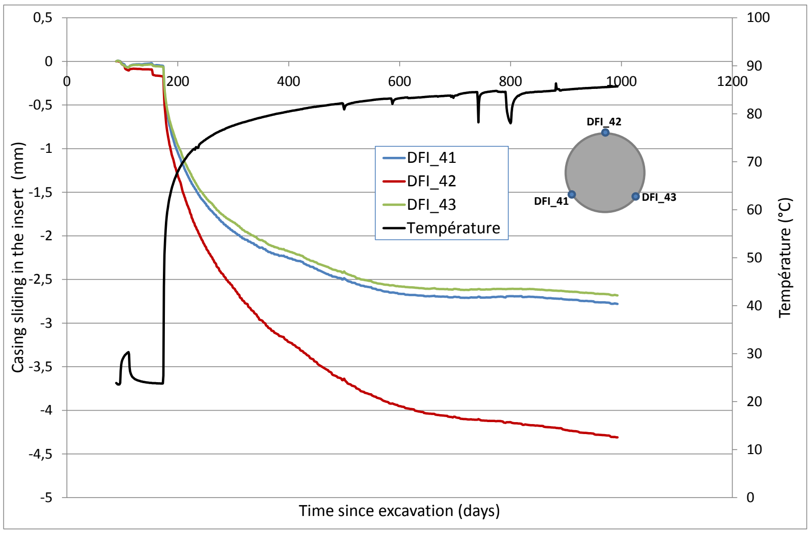


Figure 13 Sleeve sliding in the insert

1.2.6 Comparison with the models

Numerical simulations are currently being developed with the aim of helping to identify the main mechanisms involved in the evolution of the THM behaviour of the ALC1604 heated cell. The calculations are performed by ISL and UPC. In both cases the THM formulation is based on a multiple-phase approach. Hydromechanical coupling (Biot model) was used, as the thermal issue was handled separately [4][5].

The initial results of the modelling of the experiment reproduce the main trends of the rock's THM behaviour (thermal field characteristics, and pore pressure amplitude and variation direction).

Concerning the simulation of the thermal field, both UPC and ISL overestimate the near-field rock temperature in the heated zone and underestimate it in the cell head (Figure 14) despite their relatively different design choices (presence of an annular space around the entire perimeter of the sleeve sections in the useful part in the case of ISL, and direct contact with the rock in the case of UPC). However, the observed differences are not likely to hinder the overall interpretation of the experimental results. The investigations are currently continuing, with some of the main aims being to provide a better representation of the boundary conditions in drifts and to improve the description of the numerical model (taking into account the presence of a partial sleeve extrados space partly filled with rock rubble, thermal conductivity degradation in the damaged zone, etc.).

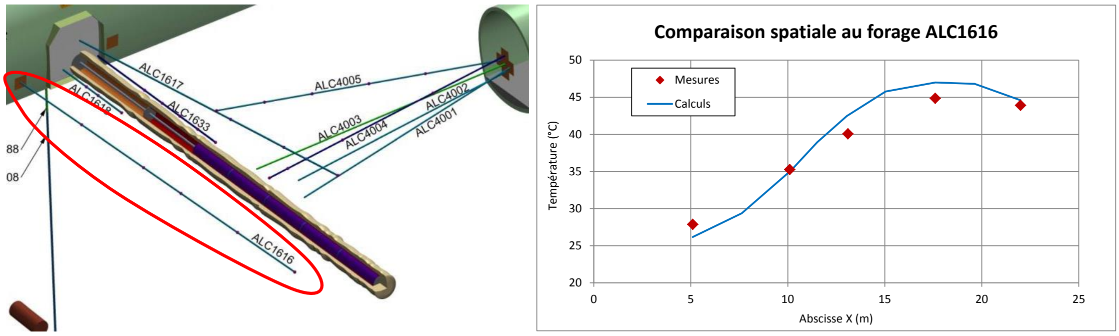


Figure 14 Comparison of the calculated (in blue) vs measured (in red) axial evolution of the near-field rock temperature in the horizontal plane after 500 days of heating (ALC1616 borehole) – simulations performed by ISL

Concerning the simulation of the near-field THM behaviour of the rock, the initial simulations performed by ISL provide a good qualitative reproduction of the main phenomena (Figure 15). Hydromechanical coupling parameter optimisation work is currently in progress.

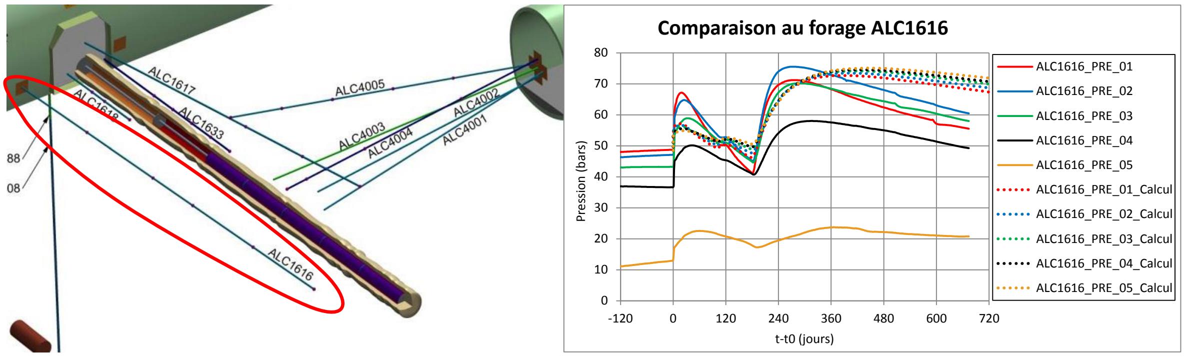


Figure 15 *Comparison of calculated (dashed lines) vs measured evolution of the pore pressures in the horizontal plane (t0 = cell excavation) – simulations performed by ISL*

Numerical simulations of the thermomechanical loading applied to the sleeve and its impact upon its deformation are currently being defined.

1.3 Impact

The ALC experiment presented in this report which is Andra's participation in the EU project LUCOEX (WP3) is a full scale HLW cell demonstration test.

It has demonstrated the construction feasibility of a HLW cell representative of the 2009 benchmark concept including a useful part and a head part. The failure of the drilling machine that occurred 70 cm before the depth target due to the blocking of the eccentrics of the cutting wheel into the 1st sleeve element did not affect either the implementation of the experiment (sleeve instrumentation and installation of the heating system) or the interpretation of the measurements. The analysis of this failure has led to modifications of the micro TBM. They consist in the improvement of the mechanical connection between the cutting head and the 1st sleeve element by adding 4 hydraulic jacks.

ALC experiment also led to a better understanding of the short term THM behaviour of the cell including the surrounding rock. Indeed this 1st full scale heating experiment provide new results on the impact of a thermal loading on the THM behaviour of the near field rock which are fully consistent with previous reduced scale *in-situ* experiments. A comparison with numerical simulations highlighted the need to optimise the calibration of the main hydromechanical coupling parameters. This work is currently in progress and it will improve the reliability of material parameters.

Concerning the short term mechanical behaviour of the sleeve, the different measurements performed on the sleeve itself and in the annular space confirm the anisotropy of the load applied by the rock. This phenomenon, due to the strong anisotropy of the excavation induced fracture network around the cell, requires us to take into account the stress corrosion cracking sensitivity of the steel in clay environment in our simulations of the long term mechanical behaviour of the sleeve.

The impact of a thermal loading on the mechanical behaviour of the sleeve has been determined for the firts time at full scale. It has been shown that the blocking of ovalization occurs much earlier than what was observed on previous full scale demonstration test despite a higher initial annular space. This phenomenon may be related to the fall of spalls due to desiccation generated by heating and/or thermal additional damage of the rock around the cell. Additional in-situ small scale heating experiments are thus already planned to identify the main mechanisms involved.

On a more technological point of view, the ALC experiment also permitted to validate the correct operation of the sliding connection between insert and sleeve to absorb its thermal expansion to limit the axial loads on the access drift wall. Measurements also show that thermal expansion of the sleeve occurs both, towards the end and towards the head of the cell. This sliding connection, which has been tested at a depth of 5 m from the access drift, can easily be moved nearer from the drift wall as required by the new concept.

Due to the evolution of HLW cell reference design, a new full scale heating experiment is planned in 2017. The main change relates to the backfilling of the initial annular space by a cement/bentonite grout whose main function is to neutralize the acid transient disturbance induced by the oxidation of pyrites in the cell wall. This phenomenon, highlighted in in-situ experiments performed on steel samples, may lead to high short-term corrosion rates. The aim of this experiment is essentially to determine the thermomechanical behaviour of the {sleeve / cement grout / damaged rock / undisturbed rock} system.

It can be concluded that the ALC experiment contributes to increase the reliability of Andra's HLW cells design, especially in regards to the impact of a thermal loading. It will also provide valuable feedback towards implementing new full scale heating experiments consistent with the new benchmark concept.

2 Acknowledgement

Andra thanks the European Union for supporting the ALC experiment with the LUCOEX-project having received funding from the European Union’s EUROATOM-research program (FP7) under grant agreement 269905 –LUCOEX.

Andra also thanks the LUCOEX partners NAGRA (Switzerland), POSIVA (Finland) and SKB (Sweden) for the continuous discussion and knowledge exchange throughout this EU project and beyond.

Andra also thanks Egis Géotechnique for the sleeve instrumentation and Aitemin for having designed, manufactured and installed the heating system.

3 References

[1] Expérimentation TED – analyse à 1 an de chauffe (TED experiment – Analysis after heating for a year) – Report DRPAMFS110039

[2] UP Alvéoles HA – essais complémentaires en forage – points d'avancement ("HLW cells" Programme Unit – Additional borehole tests – Progress report) – report DRPAMFS110092

[3] Analyse des résultats des alvéoles HA phases 1 et 1bis – (Analysis of the results for the HLW cells – Phases 1 and 1b) – report DRPAMFS110062

[4] Thermo-Hydro-Mechanical design calculations for the TED experiment – DRP0UPC090001

[5] Unité de Programme "Alvéoles HA" phase 3 – Simulation numérique du comportement THM de l'alvéole chauffante ALC1604 ("HLW cells" Programme Unit phase 3 – Numerical simulation of the THM behaviour of heated cell ALC1604) – report CRP0ISL140007

APPENDIX I - SCIENTIFIC PUBLICATIONS

- List of all scientific (peer reviewed) publications relating to the foreground of the project.

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1										
2										
3										

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication.
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

APPENDIX II - DISSEMINATION ACTIVITIES

List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project.

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	*Workshop LUCOEX*	*Andra*	*Excavation methods for drifts and HLW cells demonstrators at the Bure URL*	*2012 Mar 14-15*	*Olkiluoto, Finland*	*Scientific community and open for all*	*≈40*	*Europe*
2	*Mid-term Workshop LUCOEX*	*Andra*	*Lucoex WP3 – Full scale emplacement experiment*	*2012 Oct 25-26*	*Montpellier, France*	*Scientific community and open for all*	*≈60*	*Europe*
3	*Mid-term Workshop LUCOEX*	*Andra*	*Emplacement concept for french vitrified wastes in long horizontal micro-tunnel*	*2012 Oct 25-26*	*Montpellier, France*	*Scientific community and open for all*	*≈60*	*Europe*
4	*Mid-term Workshop LUCOEX*	*Andra*	*Mechanical load applied on a steel casing in a 500 m deep clay formation – small scale and full scale in-situ experiments*	*2012 Oct 25-26*	*Montpellier, France*	*Scientific community and open for all*	*≈60*	*Europe*
5	*Energy and Environment – ISRM*	*Andra*	*Feasibility and behavior of a full scale disposal cell in a*	*2013 Sept 21-26*	*Wroclaw, Poland*	*Scientific community*	*≈400*	*Europe*

[4] publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.
[5] Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

	Symposium Eurock 2013		*deep clay layer*					
6	*Euradwaste '13*	*SKB/Nagra/Andra/ Posiva*	*LUCOEX – Demonstrating the techniqal feasibility of disposal of spent nuclear fuel in geological formations*	*2013 Oct 14-16*	*Vilnius, Lithuania*	*Scientific community and open for all*	*≈400*	*Europe*
7	*10th Euroconference on Rock Physics and Rock Mechanics*	*Andra*	*THM behavior of a full scale disposal cell demonstrator in 500 m deep clay formation*	*2014 May 12-15*	*Aussois, France*	*Scientific community*	*≈200*	*Europe*
8	*IGDTP – Geodisposal 2014*	*Andra/Nagra*	*Full scale disposal cell demonstrators in clay formation*	*2014 June 24th*	*Manchester, UK*	*Scientific community and open for all*	*≈400*	*Europe*
9	*Clays in Natural and Engineered Barriers for Radioactive Waste, 6th International Conference*	*Andra*	*Feasibility of excavation and THM behavior of a full scale disposal cell for nuclear waste in 500 m deep clay formation*	*2015 Mar 23-26*	*Brussels, Belgium*	*Scientific community*	*≈400*	*Worldwide*
10	*Lucoex Conference and workshop*	*Andra*	*HLW cell full scale demonstration test in Bure URL: method of realization and behaviour characterization*	*2015 June 2-4*	*Oskarshamn, Sweden*	*Scientific community and open for all*	*≈80*	*Europe*

APPENDIX III – CONFIDENTIAL INFORMATION

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.

Type of IP Rights[6]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
n/a					

[6] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[7]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[8]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
n/a								

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

[6] General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[8] NACE nomenclature: http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

APPENDIX IV – EC QUESTIONAR

The following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information	
Grant Agreement Number:	**269905**
Title of Project:	**LUCOEX**
Name and Title of Coordinator:	**Jan Gugala, Project Manager SKB AB**

B Ethics	
1. Did your WP undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final work package reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Work package Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***NO***
2. Please indicate whether your WP involved any of the following issues (tick box) :	***NO***
RESEARCH ON HUMANS	
• Did the work package involve children?	
• Did the work package involve patients?	
• Did the work package involve persons not able to give consent?	
• Did the work package involve adult healthy volunteers?	
• Did the work package involve Human genetic material?	
• Did the work package involve Human biological samples?	
• Did the work package involve Human data collection?	
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the work package involve Human Embryos?	
• Did the work package involve Human Foetal Tissue / Cells?	
• Did the work package involve Human Embryonic Stem Cells (hESCs)?	
• Did the work package on human Embryonic Stem Cells involve cells in culture?	
• Did the work package on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
PRIVACY	
• Did the work package involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	
• Did the work package involve tracking the location or observation of people?	
RESEARCH ON ANIMALS	
• Did the work package involve research on animals?	
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the work package involve the use of local resources (genetic, animal, plant etc)?	
• Was the work package of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	
• Research having direct military use	
• Research having the potential for terrorist abuse	

C Workforce Statistics

3. Workforce statistics for the work package: Please indicate in the table below the number of people who worked on the work package (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	0	1
Experienced researchers (i.e. PhD holders)	1	3
PhD Students	0	0
Other	0	0

4. How many additional researchers (in companies and universities) were recruited specifically for this work package?	**0**
Of which, indicate the number of men:	

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the work package?

○ Yes
● No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	○	○	○	○	○
❑	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑	Organise conferences and workshops on gender	○	○	○	○	○
❑	Actions to improve work-life balance	○	○	○	○	○

○ Other:

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

● No

E Synergies with Science Education

8. Did your work package involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint work packages)?

- ● Yes- please specify: 3 Lucoex scholarships
- ○ No

9. Did the work package generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

- ○ Yes- please specify:
- ● No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your work package?

- ● Main discipline: 2.1 and 2.3
- ● Associated discipline: 2.2
- ○ Associated discipline:

CLASSIFICATION OF SCIENTIFIC DISCIPLINES ACCORDING TO THE FRASCATI MANUAL

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]

G	Engaging with Civil society and policy makers		
11a	**Did your work package engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*	○ ●	Yes No
11b	**If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?** ○ No ○ Yes- in determining what research should be performed ○ Yes - in implementing the research ○ Yes, in communicating /disseminating / using the results of the work package		
11c	**In doing so, did your work package involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?**	○ ○	Yes No
12.	**Did you engage with government / public bodies or policy makers (including international organisations)** ○ No ○ Yes- in framing the research agenda ○ Yes - in implementing the research agenda ○ Yes, in communicating /disseminating / using the results of the work package		
13a	**Will the work package generate outputs (expertise or scientific advice) which could be used by policy makers?** ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible) ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible) ○ No		

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**0**
To how many of these is open access[9] provided?	
How many of these are published in open access journals?	
How many of these are published in open repositories?	
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[10]: ……………	
15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the work package?	**0**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your work package has a potential impact on employment, in comparison with the situation before your work package:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	■	None of the above / not relevant to the work package
❑	Difficult to estimate / not possible to quantify		

19. For your work package partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	■

[9] Open Access is defined as free of charge access for anyone via Internet.
[10] For instance: classification for security project.

I Media and Communication to the general public

20. As part of the work package, were any of the beneficiaries professionals in communication or media relations?

○ Yes ● No

21. As part of the work package, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ● No

22 Which of the following have been used to communicate information about your work package to the general public, or have resulted from your work package?

- ❑ Press Release
- ❑ Media briefing
- ❑ TV coverage / report
- ❑ Radio coverage / report
- ❑ Brochures /posters / flyers
- ❑ DVD /Film /Multimedia
- ❑ Coverage in specialist press
- ❑ Coverage in general (non-specialist) press
- ❑ Coverage in national press
- ❑ Coverage in international press
- ❑ Website for the general public / internet
- ❑ Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

- ❑ Language of the coordinator
- ❑ Other language(s)
- ❑ English