EUROPEAN COMMISSION
Community research

(Contract Number: 232598)

WP3
Site Plans and Monitoring programmes report

DELIVERABLE (D-N°:3.1.1)

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Reporting period 1: 01/05/2009 – 30/10/2010

Date of issue of this report: **26/08/2010**

Start date of project: **01/05/2009** 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 MoDeRn project	
CO	Confidential, only for partners of the MoDeRn project	

MoDeRn

EURATOM

History Chart			
Type of revision	**Document name**	**Partner**	**Date**
First draft	MoDeRn Demonstrator Monitoring Programmes – Initial_v0d1	NDA	23/12/2009
Contribution		Aitemin	11/02/2010
Contribution		ETH Zurich	15/02/2010
Contribution		Euridice	12/02/2010
Contribution		NRG	12/05/2010
Contribution		Andra	12/05/2010
Contribution	MoDeRn Demonstrator Monitoring Programmes – Initial_v0d2	NDA	21/07/2010
Contribution		NRG	02/08/2010
Version ready for submission	**MoDeRn D3.1.1.1 Site Plans and Monitoring Programmes Report_v0d3.doc**	NDA	02/08/2010
EC submission	**MoDeRn D3.1.1.1 Site Plans and Monitoring Programmes Report v1_31082010**		31/08/2010

Distribution lists of the final version (email + acknowledgement of receipt) : DD.MM.YYYY	
Steering Committee	X
Contributors	X
Project Officer	X
Administrative and financial teams	

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1. List of Acronyms

DoW:	Description of Work
GTS:	Grimsel Test Site
MoDeRn:	Monitoring Developments for Safe Repository Operation and Staged Closure
PRACLAY:	Preliminary demonstration test for clay disposal of highly radioactive waste
TEM:	Testing and Evaluation of Monitoring Systems
URL:	Underground Research Laboratory

2. Introduction

2.1 Background

The MoDeRn project aims at providing a reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of the radioactive waste disposal process i.e. during site characterisation, construction, operation and staged closure, as well as a post-closure institutional control phase. Monitoring provides operators and other stakeholders with in-situ data on repository evolutions, to contribute to operational safety, to help manage construction, operation and/or closure activities, and may allow for a comparison with prior safety assessments. It thus provides information to inform necessary decisions. If, in addition, monitoring activities respond to stakeholder needs and provide them with understandable results, they will contribute to transparency and possibly to stakeholder confidence in the disposal process.

The project is structured into six work packages (WPs) (see Figure 1 overleaf). The first four WPs are dedicated to (i) analyse key objectives and propose viable strategies, based on both technical and stakeholder considerations; to (ii) establish the state of the art and provide technical developments to match specific repository requirements; to (iii) conduct in-situ monitoring demonstration experiments using innovative techniques; and to (iv) conduct a case study of monitoring and its integration into staged disposal, including specific scenario analysis aimed at providing guidance on how to handle and communicate monitoring results, in particular when these provide “unexpected” information.

In order to provide a shared international view on how monitoring can be developed within a given national context, WP5 regroups key dissemination activities and WP6 will provide a reference framework integrating project results and describing feasible monitoring activities, suggesting relevant stakeholder engagement activities, and illustrating possible uses of monitoring results for decision-making.

Work Package 3 consists of the in-situ demonstration of innovative monitoring technologies, conducted to further enhance the experience on which actual disposal monitoring may rely on. The aim of this package is to develop innovative monitoring techniques (Ref: Work Package 2) and to demonstrate them under realistic conditions present in underground laboratories. The main experimental part is performed in mock-ups of disposal cells to test both the effectiveness of these techniques applied to disposal situations and to understand the limits of these monitoring technologies. This approach should enhance the confidence of key stakeholders in the ability to understand/confirm the changes occurring within a disposal cell. In addition, remote monitoring technologies are investigated to better understand what is occurring in an isolated disposal cell and also to look at solutions for embedded monitoring systems in challenging (risk of damage) situations are tested. The outputs from this work will lead to improved understanding of these state-of-the-art techniques and allow focused development of those techniques beneficial to monitoring programmes. It is also planned, as part of Task 1.4, to show some of these Work Package 3 demonstrations to lay stakeholders in order to receive their feedback on the approach and their views on the value of this work. This feedback will help improve our understanding of how this work and monitoring can be more effectively communicated.

These demonstrations will rely on a combination of monitoring technologies and they will be carried out in a variety of host rocks. In addition, to contribute to a “best value for money” approach, all of these are built upon either existing infrastructure (TEM and ZigBee in Grimsel, Praclay in Hades) or will be attached to infrastructure that will be developed and financed by resources outside of this project (mock-up disposal cell in Bure). This work has synergies with WP2; State-of-the-art of relevant monitoring technology and progresses the development of state-of-the-art techniques relevant to monitoring of geological disposal.

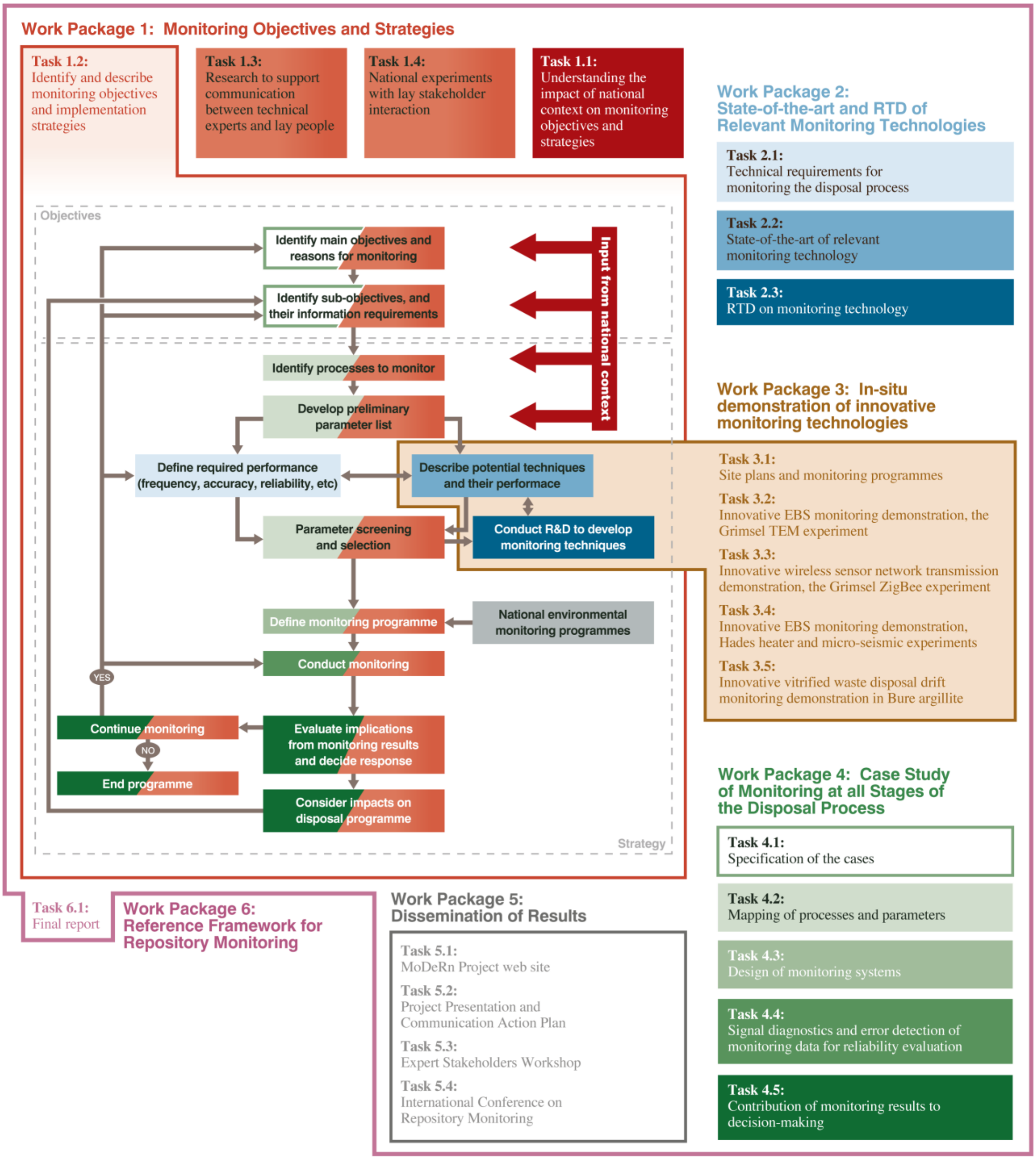

Figure 1: Relationship of the Preliminary MoDeRn Monitoring Workflow to MoDeRn Project Work Package tasks.

Value for money is an important consideration in the choices taken; for example the site at Grimsel, following completion of ESDRED Module 4 shotcrete plug construction and TEM monitoring, would be available without site development costs, to pursue and enhance the TEM demonstrator and to test the use of ZigBee wireless sensor networks. Proposed demonstration work in Hades would benefit from the infrastructure and the PRACLAY demonstrator being developed under another program. The disposal drift monitoring system installation and testing demonstrator at Bure would also benefit from a mock-up vitrified waste disposal cell to be constructed as part of a larger research program. In all of these, only those aspects specifically related to the monitoring activities would be the financial responsibility of this project. Once experiments have been finalised and designed, detailed monitoring programmes can be developed. This would include the need to develop, modify or order equipment.

2.2 Objective

This Report (Deliverable D.3.1.1) is the output of MoDeRn Project Task 3.1, which is to develop detailed site plans at all proposed demonstrators and to define equipment requirements for in-situ monitoring demonstration experiments using innovative techniques.

This report sets out the detailed programme of the proposed approach at all sites. This includes a definition of the locations for demonstration, the systems and outline configurations of the monitoring schemes complete with a more detailed programme.

2.3 Monitoring Demonstration Programmes in the MoDeRn Project

The purpose of this section of the report is to explain the specific background to the Monitoring Demonstration Programmes in the MoDeRn Project and the general objective of the Monitoring Demonstration Programmes, building on the outline in the Description of Work (DoW).

The overall aim of Monitoring Demonstration Programme is to progress, through further development, demonstration and analysis, the capability to provide an effective range of reliable and validated monitoring systems to monitor the changes occurring, particularly in those phases following isolation of the radioactive waste and the evolution of the engineered barrier system. The aim of this work programme is to apply innovative and developing monitoring techniques, including wireless and non-intrusive monitoring, to provide greater confidence in the range of techniques available and the capability and applicability of those techniques to function as required in the range of environments envisaged.

The four demonstrators planned for MoDeRn Work Package 3, are:

- Testing and Evaluation of Monitoring Systems (TEM) to be undertaken at the Grimsel Test Site (GTS) Underground Rock Laboratory (URL) in Switzerland,
- Application of ZigBee monitoring technology in the GTS URL,
- Monitoring of the PRACLAY large-scale heating experiment in the HADES URL in Belgium, using microseismic measurements, fibre-optic sensors. In addition, wireless techniques for the transmission of data from HADES to the surface will be tested,
- Integrated monitoring of a disposal cell demonstrator in the Bure URL in France.

The development of non-intrusive monitoring techniques, in conjunction with conventional intrusive or wireless monitoring techniques, in underground research laboratories (URLs), provides an effective means of calibrating a non-intrusive technique and demonstrating its performance and applicability. Obtaining comparable information through a variety of approaches leads to confidence-building in the non-intrusive technique and in its ability to provide reliable, reproducible data if implemented to monitor a repository after waste emplacement and/or post-closure.

2.4 Document Structure

The following sections of this report address each of 4 demonstrators (TEM, Zigbee, HADES, and Bure Disposal Cell) applying the following structure in each section:

- Summary
- Objectives
- Experimental Configuration
    - General Layout of the Experiment
    - Specific Layout of the Monitoring System for the Demonstrator
- Experimental Plans
- Expected Outcome

3. Testing and Evaluation of Monitoring Systems (TEM) Demonstrator

This section describes the specific objectives, experimental layout, intended operations at the TEM demonstrator site at Grimsel and the expected results.

3.1 Summary of TEM Demonstrator

Within this project, active cross-hole and hole-to-tunnel seismic methods will be investigated as a means to monitor induced changes to specially constructed features within an underground test facility.

One option for active seismic monitoring is cross-hole traveltime tomography. Unfortunately, traveltime-based methods will only be of limited value for monitoring a disposal cell, which will have dimensions of only a few metres. Regardless of the design of the site, it is very likely that the seismic velocities within the disposal cell will be substantially lower than in the surrounding host rock. Because the first arriving wave trains will predominantly "avoid" the disposal cell, they will provide no direct or only very limited indirect information about changes associated with the state of the disposal cell. Although first-break arrival times may be little affected by changes within a disposal cell, later parts of the seismic traces may provide useful information, which could be extracted using full-waveform inversion techniques.

Our aim is to demonstrate the feasibility and to develop an effective strategy to employ full-waveform inversion as a monitoring tool in the closure stage of an individual disposal cell.

3.2 Objectives

The main objectives of this project are to:

- Assess the instrumental requirements for full-waveform data,
- Assess if the requirements can be met with commercially available components, in terms information content (frequency content) and of data repeatability (fundamental for monitoring purposes),
- Analyze the effects of sources-receivers coupling to the host rock, receivers transfer functions and their effects on waveform inversion and receivers retrievability,
- Develop a modelling and inversion scheme able to cope with the high resolution required with current available computational power.

3.3 Experimental Configuration

3.3.1 General Layout of the TEM Experiment

The experimental configuration at Grimsel Test Site (GTS) URL is sketched in Figure 2 overleaf. A 1 m thick bentonite wall is assembled in layers at the end of a 3.5 m diameter tunnel. Realistic closure of the repository is simulated with a 4 m long low-pH shotcrete plug. Water introduced at a number of locations induces bentonite swelling under controlled conditions. The experimental region is equipped with several types of installed sensors that monitor a variety of parameters, including pressure, water content, temperature, deformation, etc. The sensors are mainly conventional (wired) ones but a number of them were connected to a wireless transmission system (See Section 4.3).

Since the swelling of bentonite is associated with substantial variations of its elastic properties, non-intrusive seismic monitoring was considered a viable option. For this purpose, six gently dipping boreholes were drilled at regular intervals around the circumference of the tunnel, shotcrete plug, and bentonite mass (see Figure 2 below). The length and diameter of the boreholes were 25 and 0.085 m, respectively. During each seismic measurement campaign, seismic energy was released at 0.25 m intervals along the gently dipping boreholes 3, 4, and 5. The source employed in our tests was a P-wave sparker characterized by a nominally repeatable broad-band spectrum up to several kHz, depending on its coupling to the host rock.

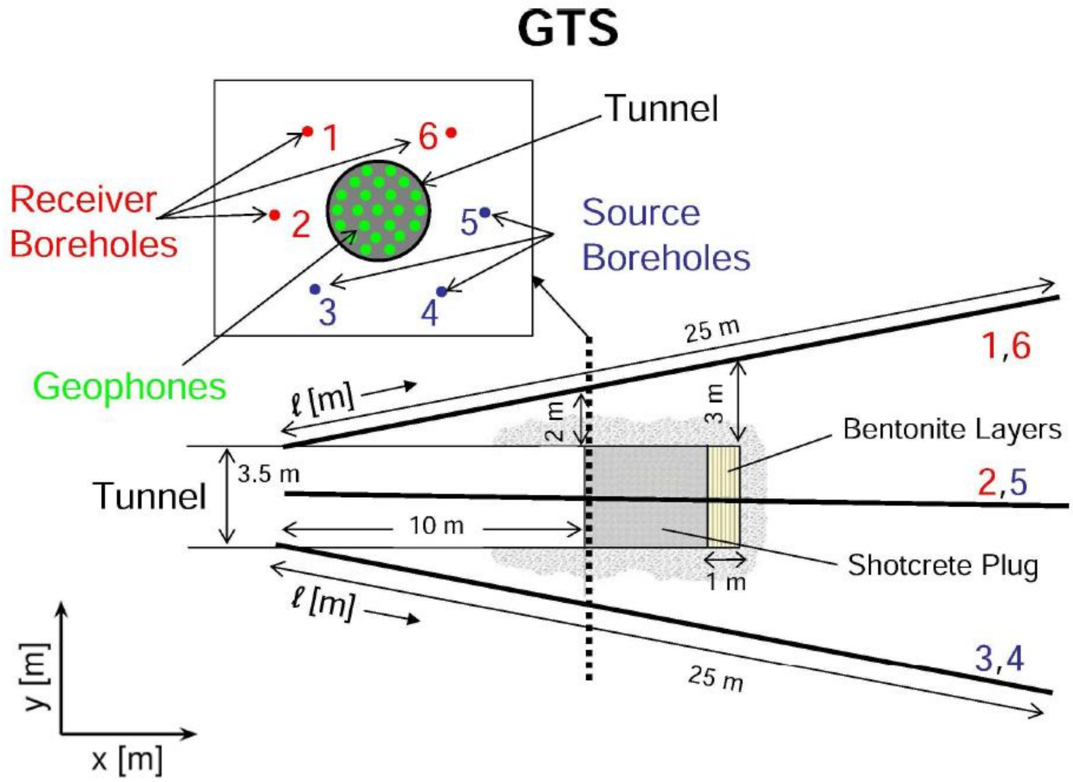

Figure 2: The experimental setup at the Grimsel Test Site (GTS).

Geological Setting *(extracted from Maurer and Green, 1997)*
The Grimsel Test Site is situated 350 - 450 m beneath the surface, within a crystalline rock body that comprises the Central Aare Granite and Grimsel Granodiorite of the Variscan-age Aar Massif. This rock body, which solidified at 300 - 290 Ma, is intersected by aplites and numerous late-Variscan lamprophyre dikes. During a phase of Alpine orogeny at 25 - 20 Ma, it was overridden by a thick sequence of northward-transported nappes and subjected to 400 - 450 ± °C temperatures and in excess of 3-kilobar pressures which resulted in green-schist facies metamorphism. At the same time, local zones of intense schistosity accompanied by faulting and folding developed in the largely massive rock body. Of the several systems of Alpine fabrics and discontinuities that affect the Aar Massif, three are dominant in the area of interest; steep-dipping bands of intense schistosity, shearing that strike roughly northeast-southwest and steep-dipping brittle structures that parallel the ubiquitous east-southeast west-northwest trending lamprophyre dikes.

3.4 Experimental Plans

The monitoring system should be emplaced in the initial phases of the disposal cell setup, immediately after the main containment chamber has been bored. This would allow the extraction of useful information about the host rock properties before the emplacement of the waste. The system should then be operated regularly after disposal cell filling and sealing.

Measurements for the monitoring can be performed by operators located in the main operation tunnel, through suitably positioned boreholes (see Figure 2 above for details). Both the source and the receivers can be replaced without interfering with the engineered barrier. Data acquisition consists of firing the source sequentially in one of the boreholes and recording the resulting wavefield at the receiver locations. Recorded data will be interpreted using a full-waveform inversion scheme, providing a 3D image of the elastic parameters in the volume between the boreholes.

The source employed in our tests is a P-wave sparker (Rechtien *et al*., 1993; Geotomographie, 2009) characterized by a nominally repeatable broad-band spectrum up to several kHz, depending on its coupling to the host rock (Lovell and Hornby, 1990).

The seismic waves are primarily recorded by an acquisition system that includes three multi-element hydrophone chains placed in gently dipping boreholes 1, 2, and 6, (see Figure 1) and a composite 24-bit dynamic range Geometrics Geode recording unit that allows 96 individual channels to be simultaneously sampled at a timing interval of 20 μs. The three hydrophone chains are each equipped with twenty-four AQ2000 sensors (Benthos, 2001) spaced at 1 m intervals. These sensors are expected to provide a flat response from approximately 0.2 to 7.0 kHz. During the surveys, 0.25 m hydrophone spacing is synthesized by shifting the hydrophone chains by 0.25 m along the boreholes and repeating the experiments. To ensure rigidity and accurate relative positioning, the hydrophone chains are placed in PVC pipes. In addition to the hydrophone data, information from twenty-four 100-Hz vertical-component geophones rigidly mounted (cemented within small holes) to the front wall of the shotcrete plug is also recorded by the Geode system.

Geophones were firmly grouted on the sealing concrete face on the operation tunnel side, and they only need to be connected to a suitable data cable to the acquisition system.
Installation of the hydrophone chains requires several steps:

- Assembly of the PVC rigid casing,
- Insertion in the receiver boreholes,
- Sealing of the borehole and receivers assemblies,
- Water filling of the boreholes,
- Connection to the acquisition system.

Correct positioning and orientation of the detectors is important in order to yield consistent inversion results. The source unit needs to be assembled and inserted into the relevant source hole. Careful handling of the source, a high power-high current device, is crucial for the safety of the operation. This study will consider how it can address repeatability through development of tools and monitoring techniques to ensure consistent inversion results.

Collected data, after proper pre-processing (filtering, noise reduction, time windowing, etc), will be processed within a full-waveform 3D inversion scheme in order to retrieve the intra-borehole volume elastic properties and their changes. Due to the high accuracy required in modelling full elastic seismic waves propagation in low velocity media (e.g. bentonite) at high frequencies, current modelling strategies require huge computational efforts. Additional strategies to reduce computational costs will have to be developed.

3.4.1 Planned Programme

Date	Activity
November 2009 – end of project	Bentonite saturation
Every 6 months, resp. when appropriate	Seismic measurements using the setup shown in Figure 2
Fall 2010	Geophone grouting trial to improve coupling
Winter 2010	Geophone array construction and grouting into one of the boreholes (if tests are successful)
Spring 2011	Geophone embedding within the concrete plug concurrent with the installation of wireless nodes under Task 3.3 (see Section 4)

3.4.2 Programme Risks

- Some problems associated with the quality of coupling in the geophones,
- Swelling of bentonite may be insufficient within the lifetime of the project,
- Computational resources for full waveform inversions may be excessive (if true 3D, elastic and possibly anisotropic wave propagation needs to be considered).

3.5 Expected Outcome

It is expected that once a suitable modelling and inversion scheme is developed, changes in the disposal cell state due mainly to water saturation of the bentonite enclosing the waste (see Villar *et al*., 2005) will be suitably monitored non-intrusively.

Besides methodological improvements in the field of seismic waveform inversions, it is also expected that significant advances in the measurement technology can be achieved. Therefore, specific recommendations if and how non-intrusive seismic monitoring should be implemented for an actual repository.

4. ZigBee Demonstrator

4.1 Summary of ZigBee Demonstrator

This activity proposes the demonstration of the ZigBee wireless sensor network when installed in the low-pH plug test, which was built during ESDRED IP project and running at the Grimsel Test Site URL. This presents a natural evolution of prior RTD activities conducted under MoDeRn Project Task 2.3 and especially of prior feasibility tests foreseen on a Spanish site.

This activity is aimed at demonstrating the potential of using wireless sensor and transmission networks underground, part of which would be immersed in solid material (buffer, concrete, rock, etc), and to manage corresponding energy needs for inaccessible immersed network sensors (nodes).

This represents an important first step to verify whether recent advances in using wireless networks to monitor surface based industry may eventually be transferred to subsurface environments. If technical feasibility can be demonstrated, future studies may then focus on the potential of using wireless networks for specific safety relevant parameters.

4.2 Objectives

The main objective of this work is to demonstrate and analyse the capability of the ZigBee wireless sensor network developed under MoDeRn Task 2.3 under realistic conditions, embedded in the engineered barrier system. A supplementary objective is to demonstrate and analyse the possibility of providing energy remotely to the isolated sensors.

4.3 Experimental Configuration

4.3.1 General Layout of the Demonstrator

The Grimsel Test Site or GTS is at an elevation of 1,730 metres above sea level, around 450 metres depth below the surface of the Juchlistock in central Switzerland. It is linked with the northern Grimsel Pass by a short approach road and a 1.2 km horizontal access tunnel which leads to the Test Site. Despite the sometimes harsh alpine winter, all-year-round operation is guaranteed by the infrastructure of the power station company (KWO) which operates a tunnel railway and an aerial cable car when the pass road is closed.

The layout of the GTS consists of a 1000 m long branching laboratory tunnel and a central building which houses the whole infrastructure such as offices, the ventilation plant, workshops and so on (Figure 3 overleaf shows the locations of the most important experiments which have been performed in the GTS). The laboratory tunnel has a diameter of 3.50 metres and was bored in six months using a full-face tunnelling machine (TBM).

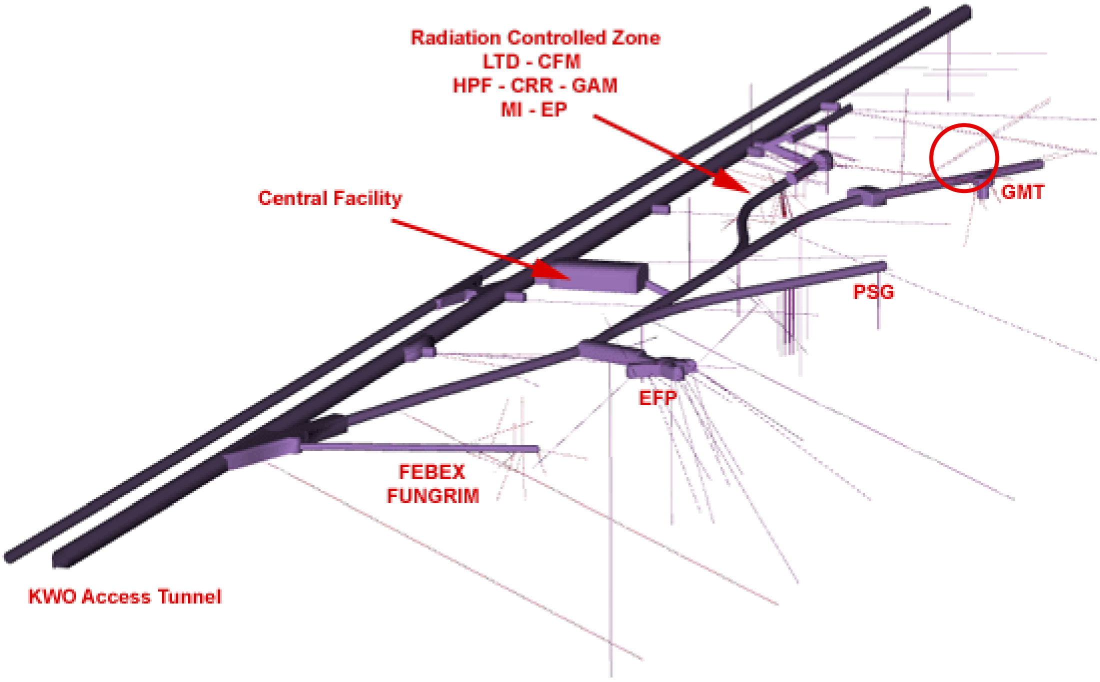

Figure 3: Layout of Grimsel Test Site (Source: www.grimsel.com) The low-pH plug test built during ESDRED IP project is located at the end of the VE tunnel, close to the GTS experiment (marked with a red circle in Figure 3 and Figure 4 below).

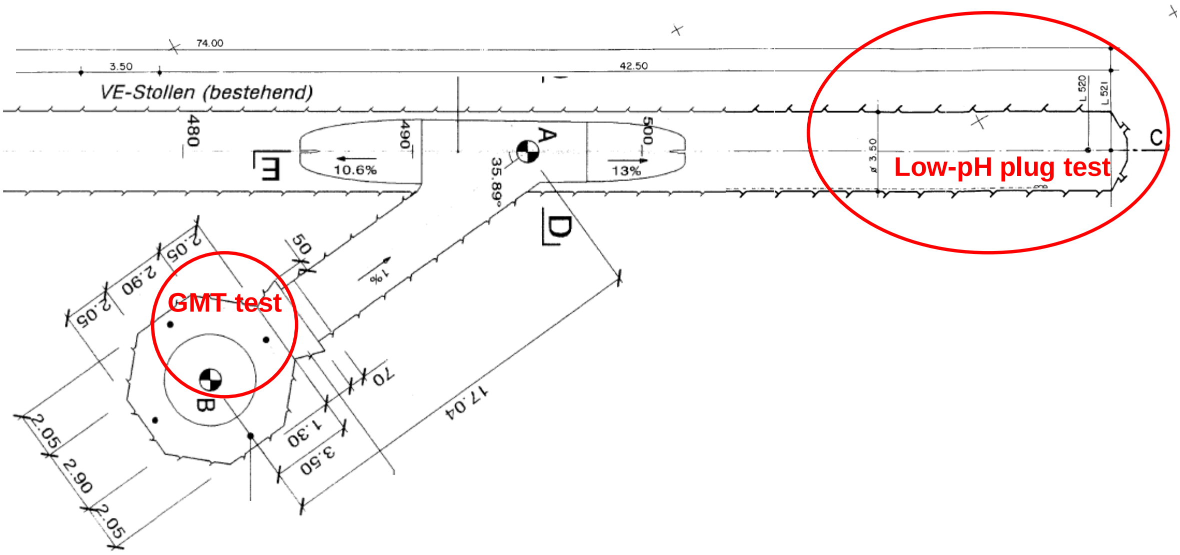

Figure 4: Location of the full-scale test at VE tunnel.

The basic layout of low-pH plug test consists of a 4 m long parallel shotcrete plug constructed at the back end of a 3.5 m diameter horizontal gallery, excavated in granite with a TBM and sealed with 1 m of highly compacted bentonite (see Figure 5 overleaf). The bentonite was provided with an artificial hydration system to accelerate the saturation process.

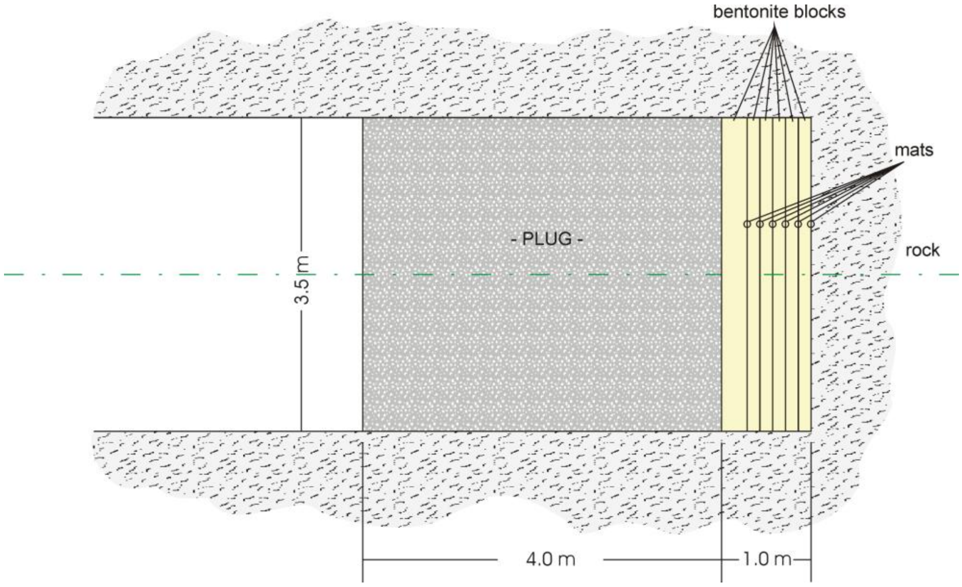

Figure 5: General layout of the full-scale test.

To monitor the performance during the test, a number of sensors were installed at different locations in the rock, in the bentonite and in the shotcrete mass: total pressure cells, humidity sensors of different types, piezometers and displacement sensors (see Figure 6 below). The sensors are mainly conventional (wired) ones but a number of them were connected to a wireless transmission system. These wireless transmitted sensors were installed as a part of the TEM Project, which is run by NAGRA at the GTS URL.

The sensors were connected, through the necessary data acquisition units, to the main DADCS for the monitoring and management of the test, which worked in unattended mode and could be contacted with modem for remote supervision.

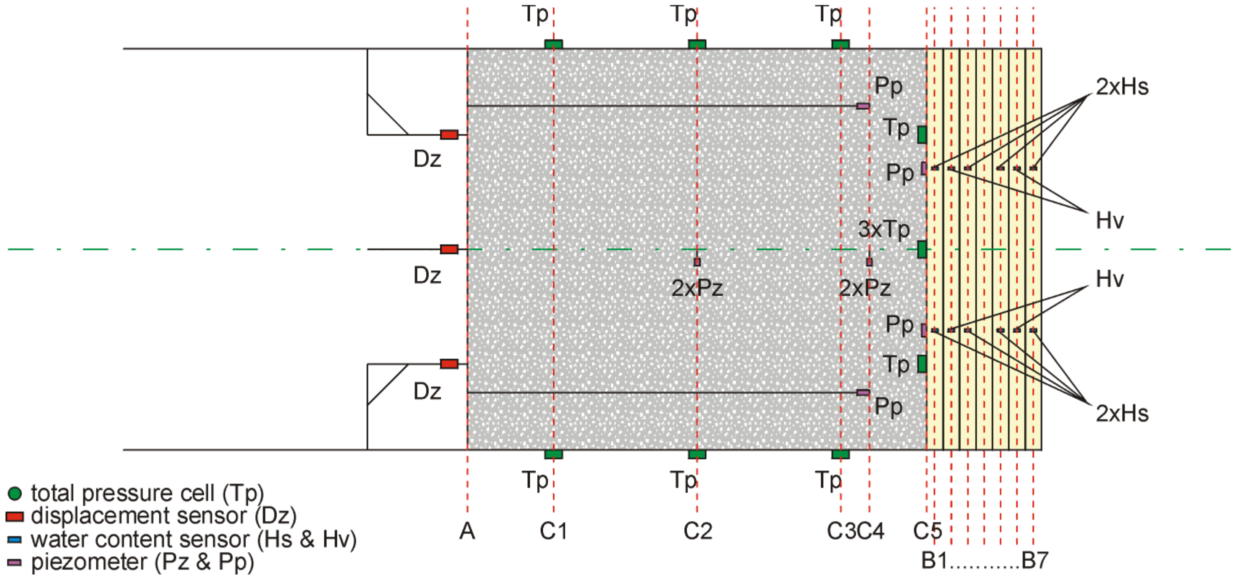

Figure 6: Layout of instrumentation (wired transmitted sensors only)

Finally, the NDA and ETH installed a non-intrusive monitoring system (See Section 3 above). It consisted in the performance, from six linear boreholes (each 25 m long) excavated around the gallery, of different series of non-intrusive seismic tomography measurements along the lifetime of the experiment. In addition, 25 single-component geophones with a natural frequency of 100 Hz were installed at the front face of the concrete plug.

4.3.2 Specific Layout of the Monitoring System for the ZigBee Demonstrator

The demonstration exercise proposed here will comprise the installation of at least five ZigBee based sensing units. Three of them will be installed in the bentonite buffer through boreholes drilled in the shotcrete plug. The parameters to measure will be: pore pressure, total pressure and water content. One of the units will be provided with a wave guide, which will be isolated inside the shotcrete plug, and another one with the system to be developed for the remote charge of batteries.

Furthermore, it is proposed to install two additional sensing units in the concrete plug and the rock mass inside boreholes drilled ad-hoc, one to measure pore pressure in the plug and another to measure pore pressure in the rock around the bentonite buffer.

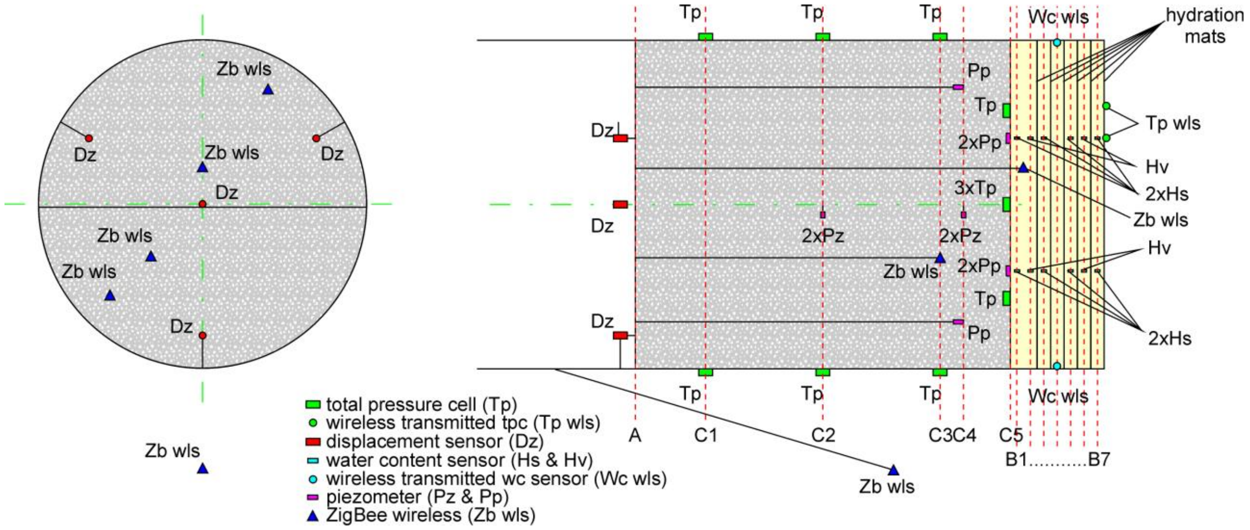

Figure 7: Layout of wireless instrumentation to be installed. N.B.: This preliminary layout could be changed upon the results obtained from WP2.

4.4 Experimental Plans

The ZigBee system will be installed after the end of MoDeRn Task 2.3 and after a period of time required for preparing the nodes for being installed at the GTS. Five boreholes will be drilled, four at the plug and one in the rock to install the five foreseen nodes. The dimensions of the boreholes and details about the installation are still not decided.

Each ZigBee node will be capable for incorporate up to four sensors: pore pressure, total pressure, humidity and temperature, providing the power supply and taking the data of all of them. The signals from the ZigBee nodes will be gathered at the open gallery and integrated into the existing AITEMIN data monitoring and control system. The data trends will be reported and compared with the already installed monitoring systems.

Several tests will be conducted:

- A first set will focus on transmission through plug performance, with or without use of a wave guide susceptible to enhance transmission distance,
- In addition, the feasibility of remote charging batteries of wireless sensor nodes will be tested.

After these tests, a small sensor node network will be set up at the site to allow for pore pressure sensors using the wireless transmission technique to be tested both in the plug and in the rock.

Overall data trends of installed wireless sensors will be compared to the other monitoring systems installed in and around the plug.

4.4.1 Planned Programme

The number, location and diameter of the boreholes to be drilled in the plug is uncertain. A solution for embedding the geophones will also be found (Task 3.2, see Section 3).

Date	Activity
November 2009	Programme of supervision, maintenance and reporting on the long plug test with a data report produced at 6 monthly intervals
February – September 2010	Laboratory Testing
March/April 2011	Installation
June 2011 – December 2012	Demonstrator Activities

4.4.2 Programme Risks

- Laboratory testing may prove technology is unfeasible,
- Unforeseen difficulties behind the practicality of installation may arise.

4.5 Expected Outcome

Several aspects of the ZigBee wireless transmission network will be studied, to test the potential for through-rock or through-plug transmission and to test possibilities to prolong battery lifetime needed for sensor operation. The analysis of the obtained results will provide valuable conclusions about the applicability and limitations both of ZigBee high-frequency based data transmission technology and selected solutions for remotely provide energy to the isolated sensors.

The main outcome will be the indication about the real capability (confidence) and applicability of such new technologies to provide an effective range of reliable and validated monitoring systems to monitor the changes occurring, particularly in those phases following isolation of the radioactive waste and the evolution of the engineered barrier system within the repositories.

5. HADES Demonstrator

Two distinct demonstration programmes are planned at the HADES URL; one utilising the PRACLAY demonstration and the other using wireless transmission from the URL to surface.

5.1 Summary of HADES Demonstrator

The first two contributions to this demonstrator are part of the PRACLAY demonstration programme being implemented in the HADES URL. The core is the PRACLAY Gallery, which is currently being equipped to simulate a disposal gallery for heat-generating, high-level radioactive waste. The third contribution is not related to the PRACLAY experiments, but is dedicated to the wireless data transmission from the HADES URL to the surface.

The demonstrator part will focus on three instrumentation aspects related to the geologically-specific conditions:

- Fiber-optic based sensing techniques; in particular (1) distributed sensing for minimal cable-feed through, (2) long-term reliability in harsh conditions, (3) extensometry,
- Micro-seismic characterisation/monitoring; in particular the potential to improve the treatment of signals to gain an understanding of (1) the evolution around the gallery due to excavation/lining and heating and (2) imaging of a water-bearing concretion layer,
- Wireless data transmission techniques from the HADES URL to the surface; in particular (1) proof-of-principle for magneto-inductive data transmission and verification of the used models, (2) optimizing of energy usage and (3) demonstration of bidirectional data transmission[1].

5.2 Objectives

Regarding the fiber-optic sensors, the demonstrator will deal with the applicability in representative conditions (except radiation) of different types of fibre-optic sensors: (1) sensing based on scattering (Brillouin and Raman) to monitor the thermal distribution along a fibre several 100's of metres in length, and (2) long-base (10 - 30 m) interferometric sensors to monitor the global gallery expansion.

The potential of micro-seismic techniques will be explored by (1) monitoring the near-field (first metres around the gallery) during the different experimental phases (gallery excavation, ventilation, saturation, and heating) by micro-seismic techniques (permanently installed piezo-electric sensors and mobile borehole impact probe), and (2) the possibilty of mapping a known discontinuity in the clay formation (range 20 m, required resolution better than 0.1 m).

For the wireless data transmission experiments from the HADES URL to the surface, the specific objective is to characterize the frequency dependent signal attenuation and to characterize and optimize the energy efficiency of the data transmission equipment considering several aspects (antenna geometry, topology, signal mode, shielding, etc).

[1] dependent on remaining time and budget

5.3 Experimental configuration

5.3.1 General Layout of the PRACLAY Demonstrator

The PRACLAY Gallery is part of the HADES URL as shown in Figure 8 below.

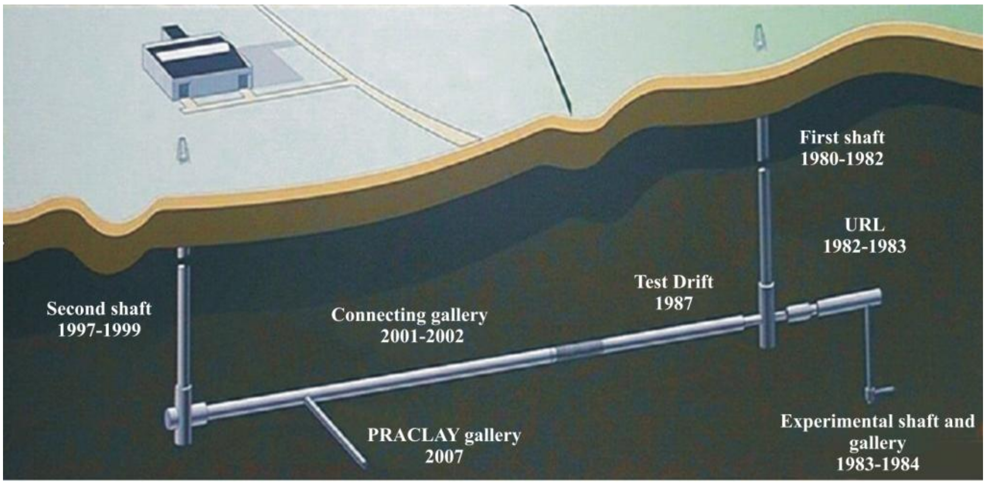

Figure 8: Schematic diagram of the layout and historical development of the PRACLAY Gallery in HADES URL.

The PRACLAY gallery is situated at a depth of 223 m, in the "Boom Clay" formation (from 190 to 290 m deep). Above this clay layer, and up to the surface, sandy aquifers are present. The clay is water-saturated (35 to 40 % vol) and porewater pressure is about 2.2 MPa. Compared with older clays, the Boom Clay (oligocene, 35 My old) is a rather plastic clay. The total stress is estimated at about 4.5 MPa. Geochemically, the clay acts as a reducing environment, and is slightly alkaline (pH = 8.2; Eh = -0.250 V). The main component of the pore water is NaHCO3 (at a concentration of about 1160 mg/l). The clay contains small amounts (1 to 5 %) of pyrite and organic matter. At district levels, concretions (septaria) are present.

All major excavations (shafts and galleries) require a structural lining. The galleries excavated in the last 10 years (Connecting Gallery in March 2002, PRACLAY Gallery in October 2007) have been lined with segments of unreinforced concrete (wedge-block system with one or two key segments). In particular, the PRACLAY Gallery, 40 m long, is lined with 30 cm thick segments, and has an inside diameter of 1.90 m. It is further being equipped with a gallery seal to separate the experimental part (to be saturated and heated – 30 m long) from the initial section in connection with the Connecting Gallery, which remains open (10 m long). At the location of this seal, the concrete lining has been replaced by a cylinder of bentonite blocks within a steel containment.

5.3.2 Specific Layout of the Monitoring System for the PRACLAY Demonstrator

The experimental part of the PRACLAY Gallery will be backfilled with sand[2] and saturated (artificially to speed up the natural hydration by the clay). After saturation, the heater is switched

[2] The underground PRACLAY test programme has been conceived as a generic experiment to investigate the effect of large-scale heating on the host rock, so concept-specific gallery design details such as backfill or supercontainer configuration are not dealt with at the underground test.

on (expected first part 2011) for 10 years. The combined heating and saturation will result in expected temperatures of about 90 °C at the PRACLAY Gallery lining inside (80 °C at the outside). In addition, the pore pressure might increase up to over 3 MPa due to the thermal coupling.

A specific layer with water bearing concretions, which is the subject of the microseismic characterisation, is situated about 10 m above the level of the galleries.

5.4 Experimental plans

(1) Fiber optic interferometric sensors (30 mB water pressure)
The (mainly thermal) expansion of the PRACLAY Gallery will be monitored through several interferometric sensors (type SOFO® from SmarTec, CH). The 30 m long span will be covered by two sensors mounted in series. At least two of these pairs will be installed. Installation is planned before the summer of 2010 and will be performed using the support structure for the heating elements. Data acquisition will be performed using a manually operated read-out system. The experimental conditions (water pressure and temperature) are the threats to the reliability of the sensors.

(2) Distributed temperature monitoring
In addition to the temperature sensors integrated in the lining segments, an optical fiber will monitor the overall temperature field inside the gallery through the scattering principle. Two physical principles are applied: Raman and Brillouin scattering. A unique fiber (mono and multimode) is installed for each principle. For installation reasons, each fiber is installed along the lining longitudinally, and will run back and forth a few times so that a total length of a few 100's of meters will be employed.

The installation is also planned before the summer break of 2010. Data collection will be performed through a rented (or on loan through ANDRA) read-out instrument – as this type of instruments are very expensive.

For both types of fiber optic sensors, data analysis is quite straightforward (the required quantity is usually displayed directly by the read-out instrument).

(3) Micro-seismic monitoring
This monitoring approach uses both fixed sensors and mobile probes. The fixed sensors are piezo-electric sensors, configured as a source (driven by high-voltage signals) or as a receiver. They are installed in three boreholes around the PRACLAY Gallery, complemented with several sensors mounted through the lining of the gallery. In addition, an extra borehole parallel with the gallery at 5 m radial distance has been lined for a mobile impact probe inside this borehole.

The fixed sensors in the boreholes have been installed prior to the gallery construction, the lining sensors in early 2008. They are currently being monitored on a daily basis (automatic mode). The system was been designed and installed by GMuG (Germany).

A pneumatic hammer probe has been used in two measurement campaigns. The idea of such a probe is to use explicitly shear waves – which should be more sensitive to the generation and healing of fractures. The signal quality and interpretation from the probe used was however not satisfying, therefore a new design (magnetically actuated instead of pneumatically) has been proposed. The design will be realised in 2010.

The characterisation of the water bearing concretion layer will also include the application of micro-seismic techniques. This is currently being investigated, and finished plans have not been put forward yet. They are expected before the 2010 summer break.

As with most geophysical techniques, data analysis and interpretation of this kind of signals is not straightforward. The current analysis of the piezoelectric sensors (velocity and damping) needs to be extended to a frequency domain analysis in addition to the time analysis.

(4) Wireless signal transmission

The wireless data transmission experiments performed by NRG are based on the transmission of very low frequency magnetic waves (optimum expected between 500 Hz and 2500 Hz) through the underground. The experimental set-up makes use of a loop antenna for the transmitter that will be matched into the existing infrastructure of the HADES URL. The experiments are divided into several steps: first, the necessary hardware will be designed and assembled and a first *proof-of-principle* will be performed in the Netherlands to demonstrate the proper working of the transmitter-receiver set-up. In the next step, the site-specific magnetic background noise at the surface in Mol will be recorded and analysed as a function of time, frequency and the direction. In the third step, the frequency-dependent signal attenuation by the geologic medium between the HADES URL and the surface, will be measured. Based on the data gained in the previous steps, optimum frequencies for the signal transmission will be derived from the background noise and the signal attenuation measurements. In the fourth step, first data transmission experiments from the HADES URL to the surface will be performed. This should not only demonstrate the proper working of the overall set-up, but should also verify the quantitative model used to calculate the necessary signal strength.

In the second part of the NRG contribution, the energy usage of the data transmission technique will be optimized. Dependent on the results obtained so far, several techniques to increase the energy efficiency may be tested, by:

- Shielding of the transmitter,
- Active elimination of localized sources of interfering signals,
- Improved signal analysis techniques,
- Improvements of signal shape or transmission modes,
- Use of array techniques.

In a last part, the bidirectional transmission of data may be demonstrated. Dependent on the results obtained so far and the remaining project time and budget, techniques for the realization of a bidirectional data transmission system will be tested that enables the interactive communication with the underground monitoring infrastructure (“talking with the repository”) and that may facilitate - besides a more efficient use of energy - the option to use the monitoring infrastructure more flexibly and efficiently and to test and maintain it.

5.4.1 Planned Programme

Date	Activity
	Galley excavated and lined
January/February 2010	Seal installation
March – June 2010	Finishing instrumentation and closing
May 2010	Heater installed
September – December 2010	Gallery saturation
January 2011	Heater switched on

5.4.2 Programme Risks

- The borehole probe has yet to be built (February 2010).

5.3 Expected outcome

The expected results will vary according to the monitoring type.

For the fibre optic sensors, we hope to get a better view on the sensor reliability (or the critical design issues) when operating in the field conditions mentioned. In addition, we should obtain a solid basis when deciding what type of distributed sensing principle to apply for temperature monitoring in/around disposal galleries.

For the micro-seismic monitoring, sensor reliability is also an issue, but the focus here will be on the data-interpretation: how to get the most relevant information from the seismic signals.

For the data transmission experiments, a methodology will be developed, that describes the most relevant aspects and parameters and can be used to estimate the minimum energy demand per bit of transmitted information for other repository locations. The contribution should also demonstrate the general feasibility of long-term wireless data transmission from a repository to the surface.

6. Disposal Cell Demonstrator

6.1 Summary of Disposal Cell Demonstrator

This monitoring demonstrator is part of a larger, combined technical and scientific programme which aims at (i) demonstrating the feasibility of construction to specifications of the vitrified waste disposal cell concept proposed in the French repository program and at (ii) measuring the hydraulic, mechanical and thermal evolutions that may influence expected performances of the disposal cell and the near-field.

The main goal for the monitoring demonstrator is twofold, namely to demonstrate:

- The capacity to conduct integrated monitoring activities inside the disposal cell, on the cell liner and in the cell near-field;
- That the designed liner monitoring system is able to withstand construction procedures and to allow for reliable liner monitoring after construction.

Construction procedures are faced with a technological challenge: Excavating a small diameter (~700 mm), horizontal tunnel and emplacing a steel liner while (i) minimizing the initial void space between cell liner and excavated host rock, (ii) maintaining friction forces between the heterogeneous rock surface and steel liner sufficiently small for emplacement, and (iii) limiting damage to the surrounding host rock to preserve its favorable properties. These construction procedures and applied stresses on the steel liner during construction present a substantial risk for liner instrumentation, which may be damaged or lost during construction. A first attempt to provide robust instrumentation is thus of paramount importance towards the feasibility of disposal cell monitoring.

6.2 Objectives

The overarching objective is to evaluate the feasibility of hydro-mechanical monitoring. The more specific, technical objectives of this monitoring demonstrator are to:

- Instrument the inside of the cell liner and the void space between liner and rock to monitor hygrometric evolutions;
- Instrument the near field to (i) identify coupled hydro-mechanical near field response to cell construction and to (ii) monitor near field hydraulic pressure evolution as the near field tends to a new equilibrium;
- Instrument the cell liner to (i) evaluate the potential of robust sensor and wiring emplacement and to (ii) detect and monitor mechanical deformations in response to the progressive liner loading by the host rock.

It should be noted that this experiment will not be heated and thus, given the robustness of the cell liner, deformations are expected to be very small, and lead to strains on the order of (or less than) ten micro-strain, which is close to the resolution of available technologies. The specific mechanical monitoring objective aims at confirming the absence of any significant mechanical liner deformation and – in the event localized deformations are larger than expected – to quantify such localized deformations.

6.3 Experimental Configuration

6.3.1 General Layout of the Demonstrator

The Meuse/Haute-Marne URL is located near the village of Bure in the East of France, on the Eastern edge of the Paris Basin. The URL is accessible via two shafts towards the main URL level at 490 m below surface, in the middle of a clay rock formation, the Callovo-Oxfordian. Ongoing construction work expands the laboratory space (i.e. accessible galleries) in which in situ experiments can be conducted. The plastic deformations of the host rock lead to a gradual convergence of the host rock around excavated openings, and all excavations require structural lining. The total stress is 12 MPa. Initial deformation and stress-relaxation around excavations lead to partial desaturation in the near field. Water influx from the rock to excavated volumes is very slow.

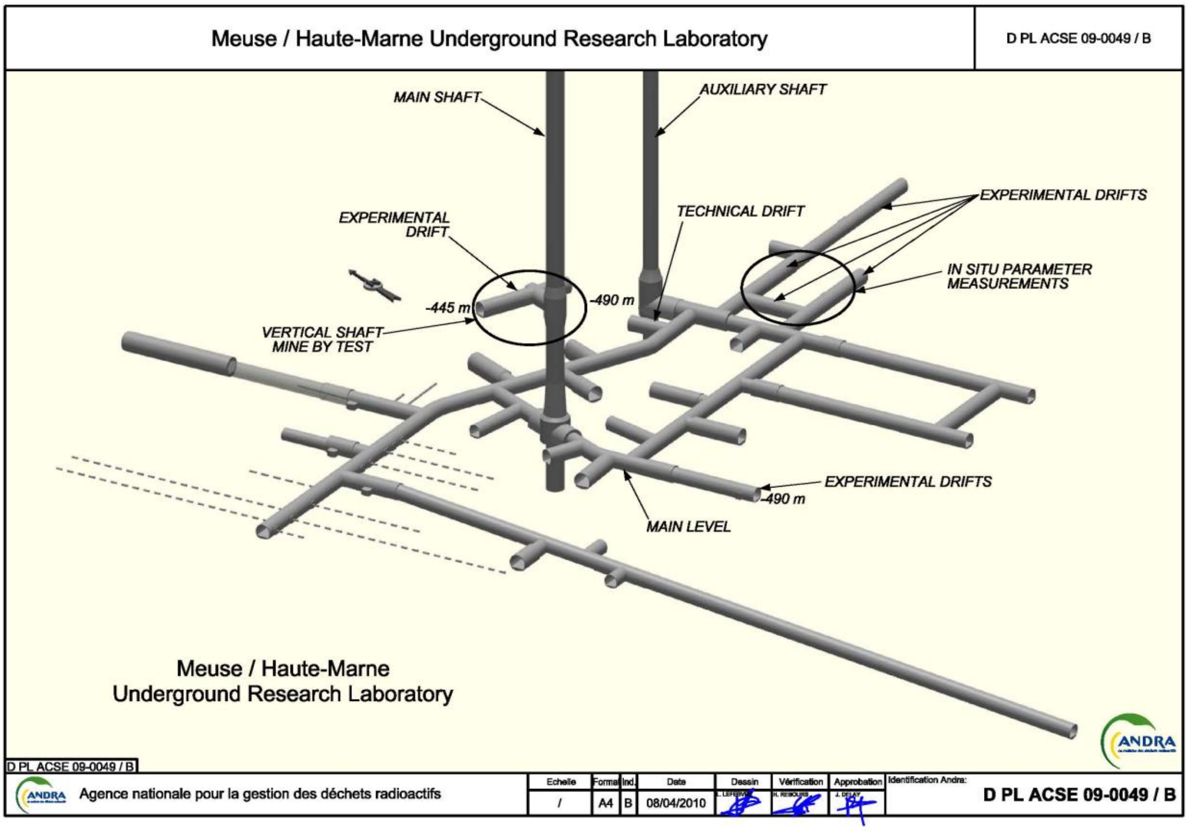

Figure 9: General Layout of Andras' MHM URL

The monitoring demonstrator is attached to the "phase 2" vitrified waste cell (*alvéole HA)* experiment and the cell to be constructed is one in a series of several such cells, with the aim of progressively improving construction technology and procedure and scientific understanding of thermo-hydro-mechanical behaviour within and in the near field of such a cell. The design for such a disposal cell is illustrated in Figure 10 below.

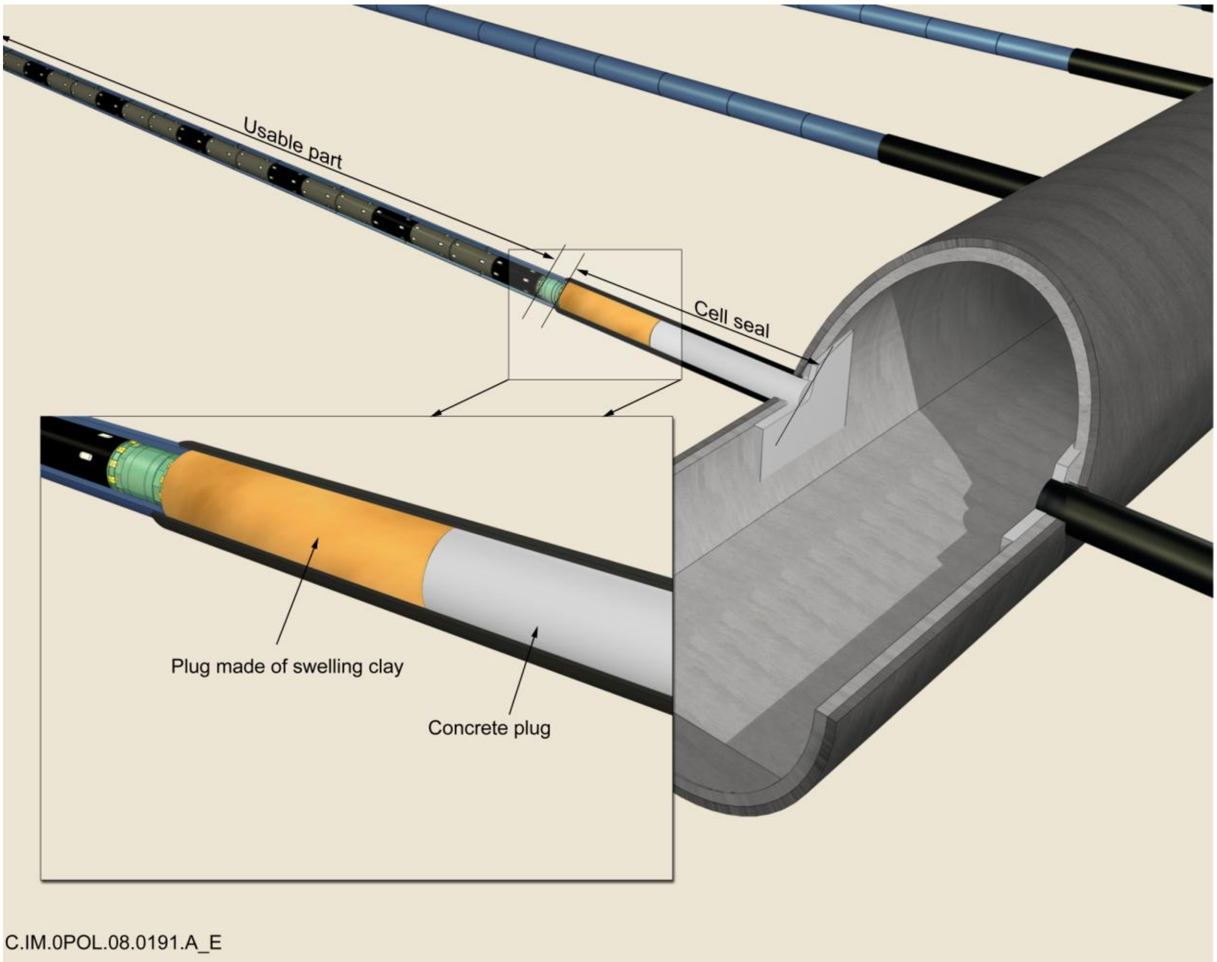

Figure 10: Vitrified waste cell concept

6.3.2 Specific Layout of the Monitoring System for the Disposal Cell Demonstrator

The construction procedure provides for excavation of a 740 mm diameter, 40 m long horizontal tunnel by a single pass, specifically designed guided auger drilling machine. Tunnel construction is initiated in a URL gallery. Emplacement of the cell liner is done stepwise, liner segment by liner segment, in parallel with excavation. Upon further excavation of a length corresponding to a liner section, the successive section of the steel liner are connected to the previous section inside the URL gallery, prior to pushing the liner further into the excavated tunnel.
The construction and general scientific investigations related to this “phase 2” waste disposal cell demonstrator provide the specific context for the monitoring demonstrator. Preliminary studies are ongoing and results and detailed decisions pertaining to monitoring equipment emplacement are expected during the summer of 2010. Actual construction and emplacement of monitoring systems is scheduled from October to December 2010.

6.4 Experimental Plans

Specific instrumentation is emplaced on the cell liner in the URL gallery, during the construction. Progressive feeding of sensor wiring and fibre optic cables is performed while protecting such wiring from potential damage that may result from further excavation and pushing of the steel liner. A preliminary design including needed protection for the monitoring system is required and close cooperation between the instrumentation and the construction crew are planned prior and during the construction.

Relative humidity will be monitored inside the first 20 m of the disposal cell. A sensor will be emplaced on each of 4 instrumented sections, which are spaced along the cell axis. This sensor will be protected by a small, perforated metal sheet to avoid damage during construction by the tunnel boring machine or by construction debris. The protective metal sheet will allow good exchange with cell ambient conditions, to ensure correct measurement of the humidity.
Liner deformation measurements will be carried out in 4 instrumented liner sections spaced over the first 20 m of the cell, at the same axial position as the relative humidity measurement. Each section includes several groups of strain gages placed both on the inside and the outside of the liner, as illustrated in Figure 11. However, the cell liner is a 20 mm thick steel tube and as such is very robust – preliminary simulations suggest that deformations will be very small. Therefore, emplaced strain gages are chosen for their relative sensitivity to very small deformations (i.e. they should be able to resolve on the order of 10 micro-strains). In addition, groups of gages are emplaced in varying directions, as illustrated in Figure 11, and are emplaced both inside and outside the liner. The question on how to emplace the gages on the inside and outside liner surface needs to be addressed. Finally, special attention is given to the choice of connecting cables, the length of cables, and how these influence the specific need for thermal compensation to avoid perturbing the mechanical strain measurements.

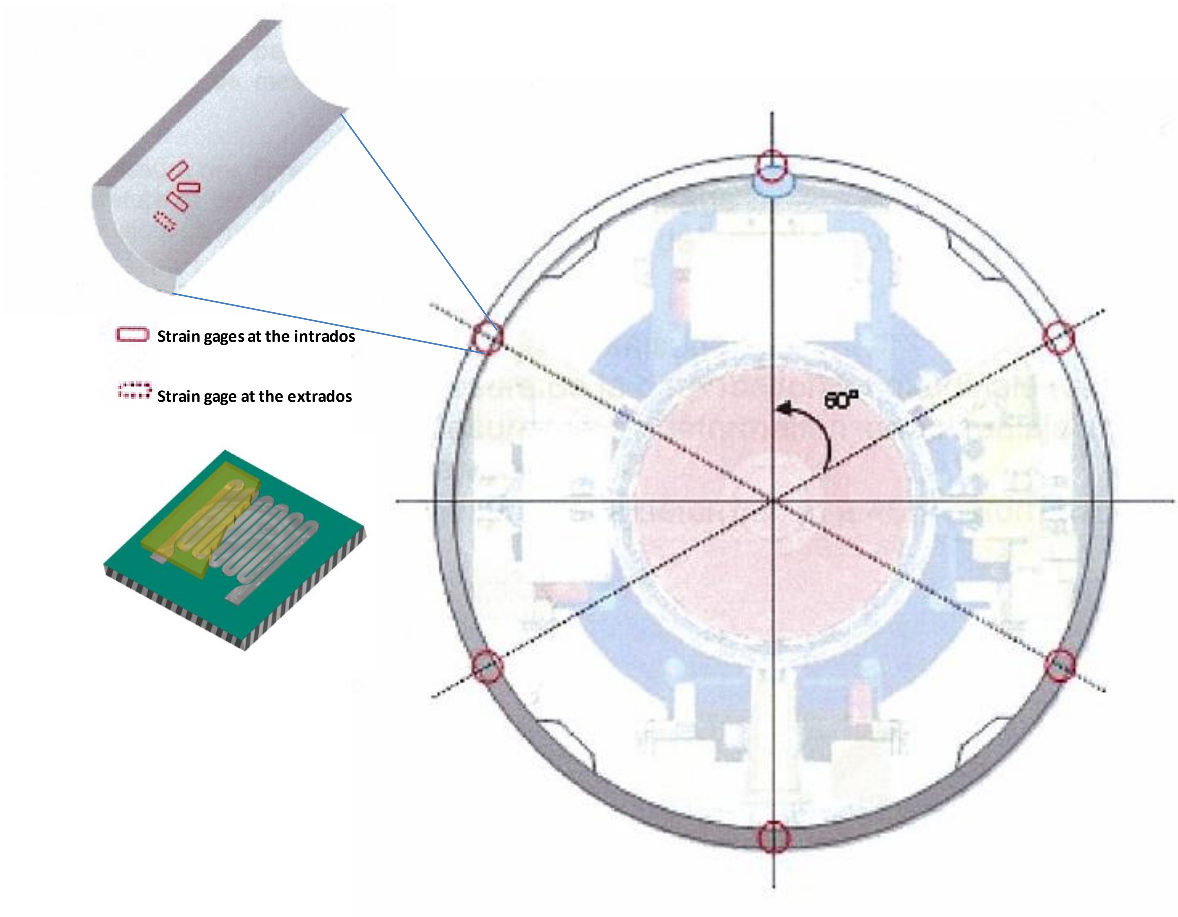

Figure 11: Displacement monitoring sensors on cell liner section

Fibre optic sensor instrumentation will be emplaced along an axis of the cell as illustrated in Figure 12 and will include necessary protection against damage, as needed. Combined thermal and mechanical strain measurements are possible by evaluating the Brillouin scattering signal inside the fibre. Instrumentation inside and, if possible, outside the cell liner is envisioned. It should be noted that both the in- and outside emplacement will require some form of protection. A compromise must be found between fibre sensitivity and robustness against possible emplacement damage.

Three outcomes are aimed for. First, when emplaced on the outside of the cell liner (pending design of an adequate protection), Brillouin sensing provides the potential to detect localized loading of the liner by the host rock. While probably not being a quantitative deformation measurement because of the relatively poor sensitivity of distributed Brillouin sensing (on the order of 30 micro-strain), this nevertheless would provide a qualitative map of the heterogeneous liner loading by the host rock. Such a map would then be used as input to reverse modelling from cell liner deformation – as measured by strain gages – to actual rock to liner loading. Second, the feasibility test of resisting construction procedure as proposed here is an important input towards designing a monitoring system adapted to vitrified waste disposal cell. Third, a true resolution of distributed, simultaneous Brillouin temperature and strain measurements is difficult to achieve. Therefore the potential of temperature compensation using a second, "loose" tube Brillouin sensor will be verified.

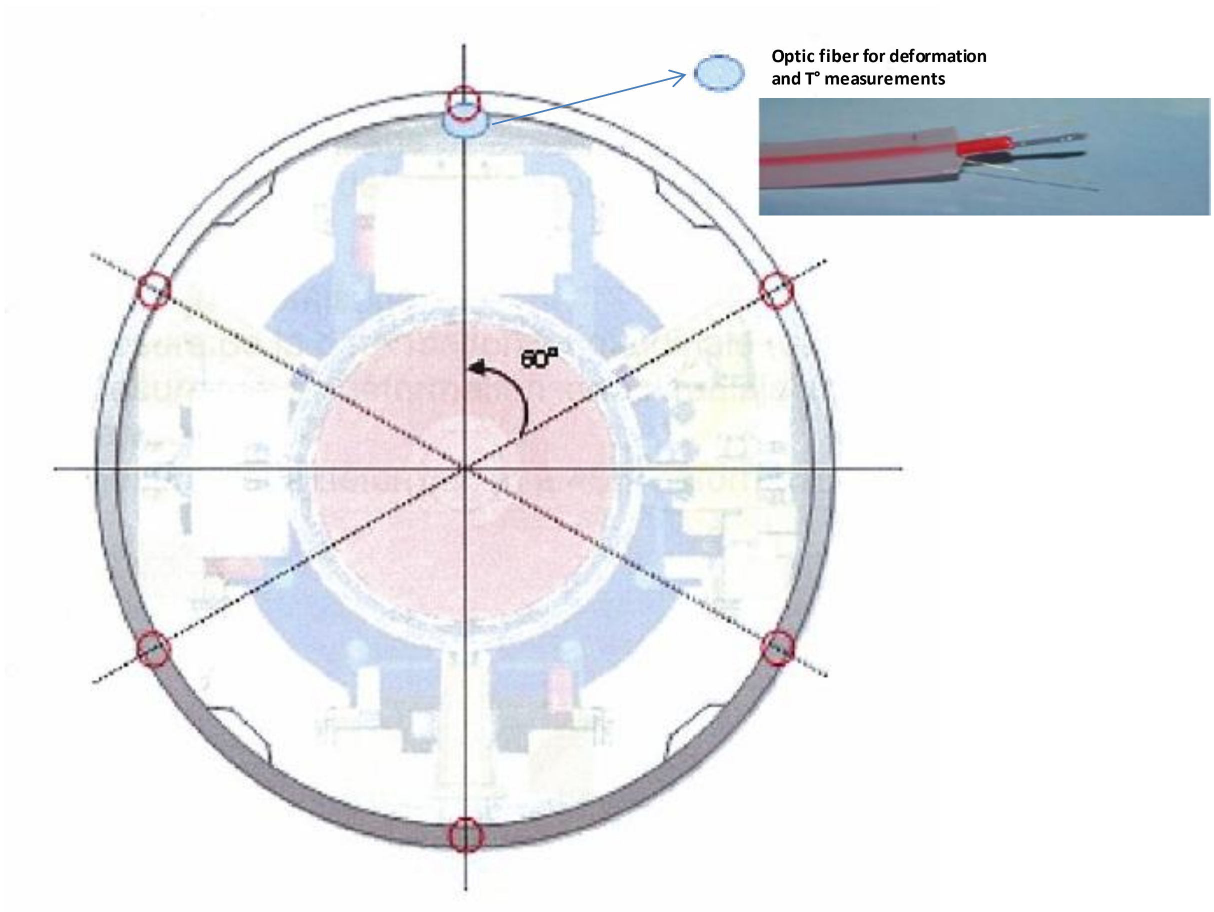

Figure 12: Illustration for fibre optic sensor position inside cell liner

The near field will be equipped with hydraulic pressure sensors emplaced in boreholes that will run subparallel to the disposal cell demonstrator and that will be constructed prior to cell construction. These sensors will monitor the hydraulic response of the near field to cell construction. An initial pressure peak is expected, followed by a pressure evolution that reflects the hydro-mechanical behaviour of the near field. In the direct vicinity of the cell, a pressure release to close to ambient is expected, as host rock deformation provides added volume for pore water, which is then followed by gradual pressure increase as the overall experiment resaturates during a period of several months to several years. At a distance not directly in the damaged zone, initial construction related pressure increase is expected to progressively decrease to tend towards a long term equilibrium of several MPa. It should be noted that the progressive deformation of the host rock near the cell liner and potential leakage of water along or inside the cell liner will influence this hydraulic pressure evolution.

All monitoring equipment will be connected to the “SAGD” data acquisition and management system in operation in the MHM URL. Among other things, this system allows for remote access to live data recorded by the monitoring equipment.

6.4.1 Planned Programme

Date	**Activity**
January 2010	Contract review meeting with cell liner instrumentation subcontractor
Summer 2010	Testing and decisions on monitoring equipment emplacement
October to December 2010	Disposal cell construction and monitoring equipment emplacement

6.4.2 Programme Risks

- The liner monitoring system instrumentation is damaged or lost as a result of stress applied to the steel liner during construction.

6.5 Expected Outcome

Expected outcomes are described in greater detail in the “objectives” and “experimental plans” sections. Overall, the expected outcome is to obtain further understanding and feedback from in situ experiments to support the design of a monitoring system that can be attached to an actual vitrified waste disposal cell. Such a monitoring system must resist construction procedures of an actual disposal cell, must resist the environmental conditions of high mechanical and hydraulic pressures, temperatures up to 100 °C, relatively high water salinity, as well as some level of irradiation. Its purpose would be to provide in situ information on thermal, hydraulic and mechanical evolutions to confirm the scientific basis used to evaluate repository safety. The outcomes of the proposed monitoring demonstrator are a step in that direction.

The results obtained from this experiment in response to the above mentioned objectives will be analysed with a view to instrumenting and monitoring a future, heated disposal cell experiment. In particular, the feasibility of robust fibre optic sensor instrumentation – if it can be achieved/demonstrated here – may play an important role in monitoring coupled thermo-mechanical evolutions of the cell liner.

7. Discussion and Conclusions

This Section provides an overview of how the WP3 activities will be integrated and the results disseminated within the MoDeRn Project.

The experiences of demonstrator activities at Grimsel, Hades and Bure, during which innovative techniques or pioneering approaches to applying proven technology are adapted to simulated repository environments, represent the practical value of the MoDeRn project. This work will help the partners to better understand how these state-of-the-art technologies can be applied to typical repository situations. Some of the situations being simulated will expose the monitoring systems to a range of harsh environments (temperature and pressure) and the experience of this WP3 programme will help shape decisions on applying monitoring techniques. The development of non-intrusive techniques will also help to provide options for more remote monitoring of disposal cells than the more conventional “hard-wired” monitoring systems. The benefit of utilising these new techniques alongside conventional techniques will be the enhanced confidence that the results can be compared with those from proven techniques.

The following reports are anticipated as a record of demonstrator activity:

- TEM demonstrator activity at Grimsel URL by August 2012,
- Zigbee activity at Grimsel by January 2013,
- PRACLAY and wireless activity at HADES URL by January 2013
- Disposal Cell Demonstrator activity at Bure URL by March 2013

These will include an appraisal of feasibility for each monitoring technique in terms of (1) implementation; i.e. the lessons learned and practical solutions to technical challenges to initiate activity, (2) data accuracy, frequency, reliability and interpretation, (3) environmental and longevity (e.g. power, hardware degradation) issues and limitations.

The information derived from practical understanding of techniques in different site specific environments will provide the basis for refining the output from Task 2.2: State-of-the-art of relevant monitoring technology and also inform more realistic expectations of technique performance (Task 2.1: Technical requirements for monitoring the disposal process). Documenting demonstrator activity will also provide a collective wisdom of what techniques are complimentary to providing increased confidence for specific parameters. This knowledge will be captured and used as evidence to support Tasks 4.2 (Mapping of processes and parameters), 4.3 (Design of monitoring systems) and 4.4 (Signal diagnostics and error detection of monitoring for data reliability evaluation).

It is also planned, as part of Work Package 1.4, to share some of these Work Package 3 demonstrations with lay stakeholders to receive their feedback on the approach and their views on the value of this work. This feedback will help improve our understanding of how this work and monitoring can be more effectively communicated.

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