EC MoDeRn Project: In-situ Demonstration of Innovative Monitoring Technologies for Geological Disposal – 12053

B J Breen[1], JL Garcia-Sineriz[2], H Maurer[3], S Mayer[4], T J Schröder [5], J Verstricht[6]

[1] ,NDA, Herdus House, Westlakes Science & Technology Park, Moor Row, Cumbria, CA24 3HU, UK – Brendan.Breen@nda.gov.uk - +441925802834
[2] AITEMIN, c/Margarita Salas 14-Parque Leganés Tecnológico-Leganés, ES-28918, Madrid, Spain,-jlg.sineriz@aitemin.es- +34914424955
[3] ETH Zurich, ETH Honggerberg, CH-8093, Zurich, Switzerland, - maurer@aug.ig.erdw.ethz.ch - +41446336838
[4] ANDRA, 1-7 rue Jean-Monnet, F-92298 Châtenay-Malabry cedex, France – stefan.mayer@andra.fr - +33 146 11 8072
[5] NRG, P.O. Box 25, NL-1755 ZG Petten, The Netherlands (schroder@nrg.eu - +31 224 568046
[6] EURIDICE EIG, c/o SCK•CEN, Boeretang 200, BE-2400 Mol, Belgium – jan.verstricht@sckcen.be +32 14 332786

ABSTRACT

Monitoring to provide information on the evolution of geological disposal presents several challenges. The 4-year, €M5, EC MoDeRn Project (http://www.modern-fp7.eu/), which commenced in 2009, addresses monitoring processes, state-of-the-art technology and innovative research and development of monitoring techniques. This paper discusses some of the key drivers for the development of innovative monitoring techniques and provides outlines of the demonstration programmes being conducted within MoDeRn. The aim is to develop these innovative monitoring techniques and to demonstrate them under realistic conditions present in underground laboratories.

These demonstration projects, applying a range of different monitoring techniques, are being carried out at underground research facilities in different geological environments at HADES URL in Belgium (plastic clay), Bure in France (indurated clay) and at Grimsel Test Site (granite) in Switzerland. These are either built upon existing infrastructure (EC ESDRED Low pH shotcrete & TEM experiments at Grimsel; and PRACLAY experiment and underground galleries in HADES) or will be attached to infrastructure that is being developed and financed by resources outside of this project (mock-up disposal cell in Bure).

At Grimsel Test Site, cross-hole and hole-to-tunnel seismic methods are being employed as a means to monitor induced changes in an artificially saturated bentonite wall confined behind a shotcrete plug. Recognising the limitations for traveltime tomography for monitoring a disposal cell, full waveform inversion techniques are being employed to enhance the capacity to monitor remote from the excavation.

At the same Grimsel location, an investigation will be conducted of the potential for using a high frequency wireless (HFW) sensor network embedded within the barrier system; this will include the possibility of providing energy remotely to isolated sensors.

At the HADES URL, the monitoring programme will utilise the PRACLAY gallery equipped to simulate a disposal gallery for heat-generating high-level waste evaluating fibre-optic based sensing techniques, including distributed sensing for thermal distribution and long-term reliability in harsh conditions. It also includes the potential to improve the treatment of signals from microseismic monitoring to enable enhanced understanding of the evolution around the gallery following its excavation due to ventilation, saturation and heating, and to image a water-bearing concretion layer.

HADES URL will also be used to test wireless techniques to transmit monitoring data from the underground to the surface. The main focus of this contribution is to evaluate magneto-inductive data transmission; and to optimise energy usage.

At the Bure underground facility in France, monitoring systems have been developed and will be embedded into the steel liner for the mock-up high-level waste disposal tunnel. The aim of this programme is to establish the capacity to conduct integrated monitoring activities inside the disposal cell, on the cell liner and in the near-field and to assess the capability of the monitoring to withstand construction and liner emplacement procedures.

These projects, which are supported by focused development and testing of the monitoring systems, will allow the testing of both the effectiveness of these techniques applied to disposal situations and to understand the limits of these monitoring technologies. This approach should also enhance the confidence of key stakeholders in the ability to understand/confirm the changes occurring within a disposal cell. In addition, remote or “non-intrusive” monitoring technologies are evaluated to provide a means of enhancing understanding of what is occurring in an isolated disposal cell. The projects also test solutions for embedded monitoring systems in challenging (risk of damage) situations. 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 future monitoring programmes.

It is also planned, as part of the MoDeRn programme of stakeholder engagement to show some of these monitoring demonstrations to lay stakeholders in order to receive their feed-back on the approach taken and their views on the value of this work. This feedback will help improve our understanding of how this work and future work on monitoring can be more effectively communicated.

The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° 232598.

INTRODUCTION

To successfully implement a programme for repository monitoring requires a competent technical programme focused on providing monitoring information in a clear and transparent manner. The main goal of the EC MoDeRn Project (**Mo**nitoring **De**velopments for safe **R**epository operatio**n** and staged closure) is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring.

The MoDeRn project aims to provide 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 also be used assess against safety assessments. Monitoring provides information to inform decisions during the stages of repository development, operation and closure. When monitoring activities respond to stakeholder needs and provide them with results that can be readily understood, they will also contribute to transparency and help develop stakeholder confidence in the disposal process.

The MoDeRn Project work programme addresses both *Process* (why monitor, developing a monitoring programmes, translating monitoring objectives into practice and using the results from monitoring) and *Technology* (technical requirements and constraints, state-of-the-art for monitoring technology, focused R&D and the development of techniques through demonstrations in URLs). The projects work includes the development of three sample *Case Studies*, addressing monitoring in 3 geological environments (granite, clay, salt). A paper addressing *Process* [1] and another paper addressing one of the *Case Studies* (salt) [2] will be presented at this conference. The MoDeRn project aims to provide implementing organisations and other interested parties with a framework and examples of how a monitoring programme could be developed. The *Technology* programme within MoDeRn aims to establish: the current status of monitoring technology relevant to geological disposal and to advance the capabilities and understanding of monitoring systems through further research, development and demonstration of appropriate monitoring techniques. Although the MoDeRn partners acknowledge that there are a wide range of monitoring activities required at a geological disposal facility (GDF) e.g. construction and operational safety, environmental monitoring etc., the partners have recognised and focused on those techniques applicable to disposal cell monitoring as these were viewed as both challenging and relatively unique to geological disposal.

OBJECTIVES

The objectives of the MoDeRn Project *Technology* programme are to provide an up-to-date position on relevant monitoring technology and to advance the capabilities and understanding of specific and relevant monitoring techniques through research, development and demonstration using mock-up disposal solutions in underground research laboratories (ULRs).
The *Technology* programme includes the following activities:

- Identification of the technical requirements for monitoring programmes;
- A workshop engaging a range of monitoring skills from technical applications outside of but relative to geological disposal (e.g. oil and gas industry, carbon capture and storage, mining and civil engineering);
- To develop a state-of-the-art report, using the information from the workshop, from wider research and from the expertise of MoDeRn team members; and
- *In situ* demonstrations of identified innovative monitoring techniques focused on disposal cell monitoring to refine and enhance these techniques and to understand the capabilities and limitations of these systems and how they might be applied in addressing design, operation and closure of a GDF.

Brief descriptions of each of the technical demonstrators are included in this paper and the plans and programmes are addressed in more detail in Ref [3] which can be found on the MoDeRn website (http://www.modern-fp7.eu/) Reports on all the work on technical demonstration will be prepared towards the end of the MoDeRn project scheduled for 2013.

TECHNICAL REQUIREMENTS AND STATE-OF-THE-ART

MoDeRn partners prepared a document [4] providing an overview of the technical requirements that will likely need to be addressed when developing, selecting and implementing monitoring technologies suitable for the geological disposal of radioactive waste. This document recognised that many of the national programmes are at an early stage where sites and or specific host rock types have not yet been identified. These “technical requirements” are not therefore viewed as “mandatory - obligation to implement”, recognising that as designs develop these requirements might change. Identifying these requirements then enables an assessment of applicable monitoring techniques which could be applied.

MoDeRn partners also recognised the value of assessing monitoring applications in technical fields outside of geological disposal and brought together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art techniques to monitoring. The specific objectives of the workshop, held in Troyes, France in June 2010, were to:

- Review recent developments in monitoring technologies.
- Stimulate a mutually beneficial exchange of experiences, applications and views between the radioactive waste management community and monitoring technology experts from other fields.
- Facilitate knowledge transfer, e.g. identify EC projects and other international projects with a monitoring component.

Fourteen presentations were given in five technical sessions and 21 posters were exhibited and discussed in 3 poster sessions. Each technical session was followed by discussion sessions covering:

- Overview of Applications and Technologies.
- Geotechnical and Hydrogeological Monitoring.
- Sensor Networks and Fibre Optic Sensors.
- Air-based and Satellite-based Monitoring Technology.
- Non-intrusive Monitoring and Wireless Transmission.

The conclusions from the workshop [5] were:

- Wireless sensor networks (WSNs): Battery power limits the operation of WSNs to 1-2 years. Data processing techniques can reduce the quantity of data requiring transmission by 99%, which may lead to increasing effective operating time to 10 years.
- Wireless through-the-earth transmission: Current developments suggest the feasibility of direct transmission of a limited amount of data from the repository to the surface, over a period of one or several decades.
- Fibre optic sensors: Fibre optic sensors are available for the measurement of temperature and strain, with some capability for measuring these parameters on a distributed basis. Glass optical fibres can measure strains of 1%, whereas polymer optical fibres can potentially measure strains up to 40% and have been demonstrated to measure strains up to 20%.
- Seismic interferometery: Developments in coda wave analysis allow for the monitoring of temporal changes in the average properties of a medium (e.g. pressure as a result of thermal expansion) of ~0.1% – 0.01%.
- Time-lapse 3D seismics: Estimates of the volume of CO^2 imaged on 3D seismic surveys of the Sleipner Field in the North Sea accounts for 85% of the injected CO^2.
- Acoustic emissions and microseismicity (AE/MS): AE/MS events have been monitored in response to changes in pressure (of 4 MPa) and changes in temperature (of 6°C) in underground research laboratories.
- Borehole multiple completion methods for fluid pressure measurement have recently been extended to depths of ~2,400 m and instrumentation has been upgraded to allow measurement of pressures up to 5000 psi.
- Strain monitoring using extensometers and tell-tales: Tell-tales can monitor millimetre-scale displacements in tunnels.
- Stress monitoring: Installation of multiple point systems prior to tunnel excavation can detect the impact of excavation on the in situ stress up to 100 m from the tunnel. Monitoring of coupled stress and deformation in a range of underground settings has illustrated that

stress can be used as a good indicator that deformation might happen; a sensor has been developed that auto-corrects its “0” point.
- Laser scanning: Laser scanning has been used to develop 3D models of underground excavations that can resolve features as small as 5 mm in diameter, with 3-5 cm spatial accuracy, when the laser scanning devices are placed up to 1 km from the target.
- Satellite imagery: Optical imaging technology is readily available with a 50 cm resolution.
- Radar interferometery: Corner Reflector Interferometric Synthetic-aperture Radar (CRInSAR) provides millimetre-scale monitoring of changes in ground elevation.

The information from this workshop coupled with the expertise and research of the MoDeRn partners will be used to compile a state-of-the-art on monitoring for geological disposal which will be published towards the end of the project.

SEISMIC TOMOGRAPHY

Seismic tomography has been identified as a potentially useful option for non-intrusive monitoring. Standard travel time-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.

A powerful alternative to travel time tomography is offered by full waveform inversions, where the information content offered by the entire seismic records is exploited. Although this technique has been known for more than 20 years, it has only recently received a lot of attention in the exploration industry. This is mainly due to the fact that substantial computing resources are required for performing the inversions.

Monitoring disposal cells with seismic waveform inversion methods requires a number of specific problems to be addressed.

1. Changes within the disposal cell are expected to produce only very subtle changes of the seismic waveforms. Therefore, highly accurate and repeatable measurements need to be performed.

2. Seismic waveform inversions resolve changes of the elastic properties of the medium under investigation. These variations of the elastic properties need to be “translated” into physical processes. For example, water saturation of bentonite, which is typically employed for embedding high level radioactive waste, results in swelling and thus changes to the elastic parameters. To estimate the degree of water saturation from seismic measurements, it is necessary to perform controlled laboratory measurements to relate the degree of water saturation with the corresponding changes of the elastic parameters.

3. A typical monitoring setup of a disposal cell requires a 3D problem to be solved. To date, 3D elastic waveform inversions are not yet feasible, but 3D acoustic inversions (a simplified version of the elastic case) can be handled by modern computer clusters. Tests are required to assess whether the acoustic approximation is applicable to monitoring disposal cells.

4. The high seismic contrasts between the disposal cell and the surrounding host rock produce strong non-linearities. This may cause standard inversion algorithms to be unsuccessful.

An experimental test site has been established at Grimsel Test Site (GTS). The layout is sketched in Figure 1. 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. Six gently dipping boreholes were drilled at regular intervals around the circumference of the tunnel, shotcrete plug, and bentonite mass. 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. The seismic waves were 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. 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.

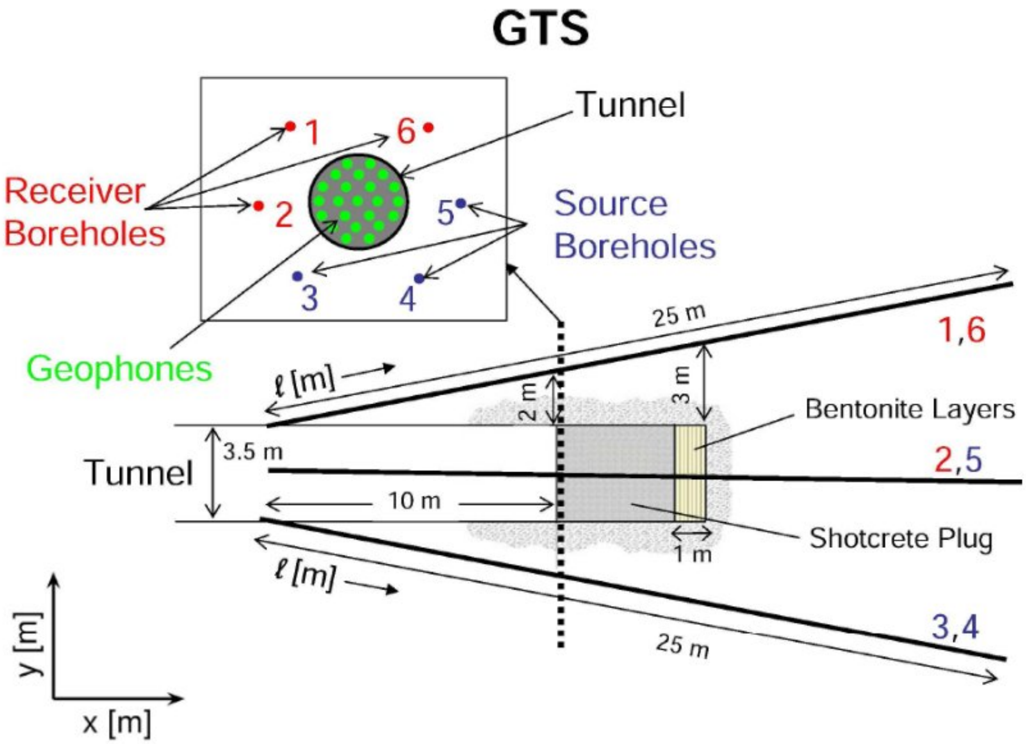

Figure 1: The experimental setup at the Grimsel Test Site (GTS).

HIGH FREQUENCY WIRELESS SENSOR NETWORKS

This activity is aimed at demonstrating, under realistic conditions, the potential for underground use of high frequency wireless (HFW) sensors and transmission networks, part of which would be immersed in solid material (buffer, concrete, rock, etc), and the management of the corresponding energy needs for inaccessible immersed network sensors (nodes).

Experimental Configuration

The demonstrator is being developed at the Grimsel Test Site (GTS), an underground research laboratory (URL) excavated in the crystalline rock of the Swiss Alps. The layout of the GTS consists of a 1000 m long branching laboratory tunnel and a central building which houses the whole infrastructure.

The demonstrator is located in an existing long term experiment, so called long low-pH plug test, which consists of a 4 m long parallel shotcrete plug constructed at the back end of a 3.5 m diameter horizontal gallery, and sealed with 1 m of highly compacted bentonite (see Figure 2). The bentonite was provided with an artificial hydration system to accelerate the saturation process. To monitor the performance during the test, a number of conventional (wired) sensors were installed at different locations in the rock, in the bentonite and in the shotcrete mass. This setup is closely representative of the expected conditions at the repository.

The demonstration exercise comprises the installation of five HFW sensor nodes, two of them installed in the bentonite buffer through boreholes drilled in the shotcrete plug and three more units to remain in the shotcrete plug and the rock mass inside boreholes drilled ad-hoc. The parameters to measure will be: pore pressure, total pressure and water content.

Development work

The basis for the construction of the HFW units was developed under MoDeRn Task 2.3 (R&D). Each HFW node is capable to incorporate up to four sensors: pore pressure, total pressure, humidity and temperature, providing the power supply and gathering the data from all of them. The signals from the HFW nodes will be gathered at the open gallery and integrated into the existing data monitoring and control system (DAS). The data trends will be reported and compared with the already installed monitoring systems.

Progress achieved

The construction of the HFW nodes for demonstrator comprised the design of a new housing, adapted to the installation conditions, and provided with the measuring sensors. After a period of time required for preparing the nodes for the installation at the GTS, the boreholes were drilled, four at the plug and one in the rock, corresponding to the five foreseen nodes. A small sensor node network was set up at the site by installing the nodes into the boreholes, and data is being collected at the existing DAS.

Outline program

Several tests will be conducted:

- A first set will focus on transmission through plug performance,
- In addition, the feasibility of power harvesting for wireless sensor nodes could be tested in the future.

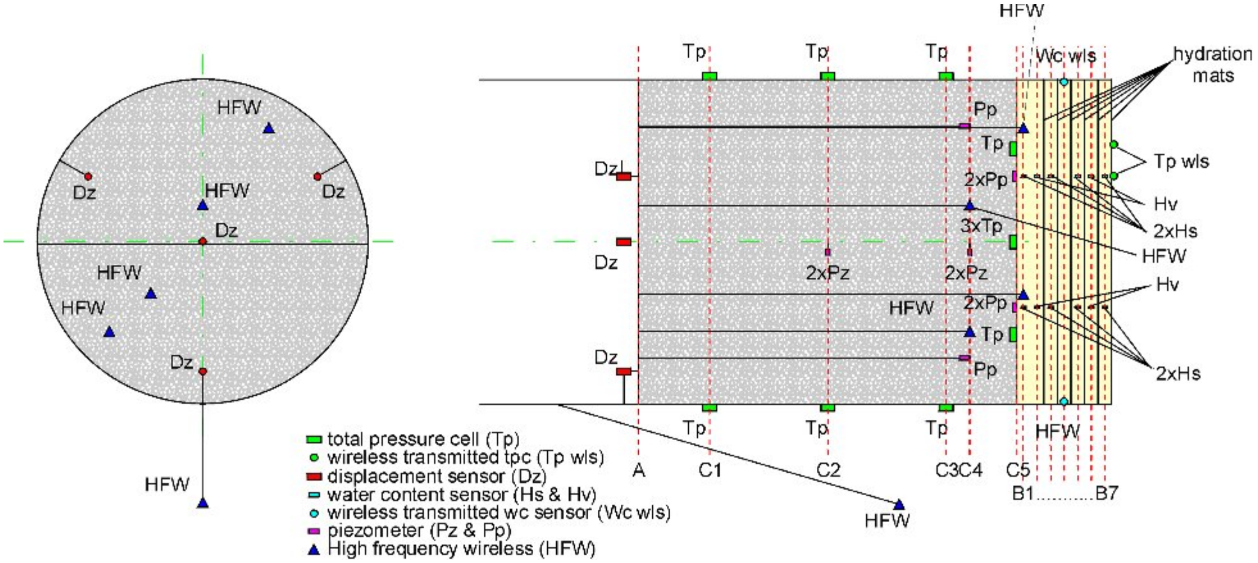

Figure 2: General layout of the long low-pH plug test including the HFW units

FIBRE OPTIC SENSING

The PRACLAY Gallery at the HADES URL is currently being prepared for the heater switch-on, starting a 10-year long experimental period to simulate the heat dissipation of a HLW disposal gallery at near-real scale. This large experimental set-up includes an extensive instrumentation programme, mostly consisting of sensors with a proven track record such as thermocouples and vibrating wire strain gauges. Several hundreds of sensors have been installed in the clay host rock around the gallery, inside the gallery lining, as well as inside the gallery itself – resulting in an impressive cabling lay-out with multiple feed-throughs at the seal, where the experimental part of the gallery is closed off from the part that will remain accessible.

In addition to these well-known sensors, some rather experimental monitoring techniques, based on fibre optic technology, have been implemented – not only for monitoring purposes, but also to assess their potential in repository conditions for long term conditions. Large numbers of cables are likely to be avoided in real repository conditions, and fibre optic technology allows the number of cables that have to pass seals or barriers to be minimised, whilst a large number of points can still be monitored – particularly through distributed monitoring.

In the PRACLAY programme, we apply fibre optic sensing for two applications: temperature monitoring along a fibre using distributed monitoring, and long-base extensometry through interferometric sensors.

1. Distributed sensing

The monitoring approach of distributed sensing is based on "the fibre is the sensor". Basically, this only requires the installation of a fibre inside the medium, where only access is needed to both ends of the fibre. With a typical fibre having a diameter less than 1 mm (including cladding and basic coating layers), we opted for the installation inside a steel instrumentation tube, giving a good protection and, in principle, allowing the replacement of the fibre.

Instead of purchasing a readymade fibre, we started by blowing a high-temperature monomode fibre (with polyimide coating instead of the usual acrylic coating) inside a 2 mm internal diameter stainless steel tube over a distance of more than 50 m. Next, we installed this instrumented tube loopwise inside the gallery so that both ends of the fibre are accessible and equipped them with connectors. For distributed temperature measurements along a monomode fibre, two physical principles are available: Brillouin scattering and Rayleigh backscatter. Due to the in-house available expertise, we have started with the Rayleigh technique and currently, reference measurements have been made at ambient temperature. Due to the basic nature of these measurements, extensive analysis is required to calibrate the sensors and to compensate for strain-induced errors – as both measurement principles are also affected by strain in the fibre.

The same measurement principles will also be applied to optical fibres that have been installed along boreholes in the past – and which will also experience a heating once the PRACLAY Gallery heater has been switched on.

In a later stage, once stable conditions have been reached, we will also try to replace a fibre. Using a mock-up installation to optimise this technique is a possibility considered.

2. Extensometry

Because of the difficulty we have experienced in the past of monitoring extensions over larger base lengths (several 10's of m) through conventional extensometers (e.g. rod-based extensometers) – in particular in a clay environment, we have looked towards fibre optic techniques to monitor this quantity. The extension (or compression) of the 30 m-long PRACLAY Gallery due to external loading or temperature expansion is monitored through SOFO® sensors, that can monitor length variations down to a few microns over distances up to 10 m. Three sensors have been installed in series to cover the whole length of the heated gallery. These commercially available sensors have also been installed in three boreholes that have been drilled from the PRACLAY Gallery up to a depth of 20 m to monitor the (thermal) expansion of the host rock following the heating in the PRACLAY Gallery. Each borehole contains three sensors to obtain a multipoint borehole extensometer. The sensors were installed in flexible tube for protection and to allow for installation (e.g. upward borehole). The sensors consist of two fibres inside a protective tubing, with one fibre being attached to two anchor points at both ends of the tubing, and another fibre of similar length which is loose inside the tubing – and whose length is therefore not influenced by the change of length between the anchor points. The difference between the two fibres is then monitored by interferometery.

The experimental conditions (in particular hydraulic – with water pressures up to almost 3 MPa) are harsher than the standard version of the sensors can resist, and therefore an additional protection has been designed (typically based on epoxy potting and additional mechanical protection) to increase the chance of survival of these sensors in the saturated and heated gallery and host rock.

These sensors will teach us more about the adaptations that are needed for this kind of sensors. Particular aspects are the fibre protection needed (including connectors), influence of this protection on the measured quantity, and thermal influence on the sensor.

WIRELESS DATA TRANSMISSION

In the event that monitoring of the underground disposal should be required after closure, an autonomous monitoring system is necessary that enables the wireless transmission of data from the repository to the surface. To transmit data over a relevant distance through geologic media (e.g. 500 m for the Dutch reference repository), only a limited number of principal techniques are feasible. Within the MoDeRn project, NRG is conducting tests on the wireless transmission of monitoring data using low frequency magneto-induction techniques. These techniques are applied e.g. in mine communication and rescue (“trapped miner detection”) or military communication. The specific objective of NRG’s contribution is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring. This should also help demonstrate the general feasibility of long-term wireless data transmission from a repository to the surface through overlying layers of Boom Clay and aquifers.

The wireless data transmission experiments are being performed at the HADES Underground Research Laboratory in Mol, Belgium, situated at 225 m depth in a 100 m thick layer of Boom Clay. The HADES URL is assumed to be representative for the Dutch situation, because the properties of the Boom Clay and the overlying aquifers is expected to attenuate the magnetic fields more strongly than other host rocks e.g. granite, salt rock or Opalinus clay.

In 2010, the principal experimental set-up and experimental boundary conditions have been established: first, the necessary hardware was designed and assembled and a first proof-of-principle was performed in the Netherlands to demonstrate that the transmitter-receiver set-up was functioning as expected. The site-specific magnetic background noise pattern at the surface in Mol was then recorded and analyzed as a function of time and frequency. Then the frequency-dependent signal attenuation by the geologic medium between the HADES URL and the surface was determined. During the experiments, signal transmission from the HADES to the surface was demonstrated at several frequencies. As expected, due to the high electrical conductivity of the subsurface, a strong attenuation of high frequencies appeared; this limited the available bandwidth for data transmission to less than 2 kHz. Based on the data gained in the previous steps, optimum frequencies for the signal transmission have been derived on basis of the background noise and the signal attenuation measurements.

In 2011, additional measures and experiments have been performed in order to characterize and test relevant element of the transmission chain and to optimize the energy use of the set-up. A theoretical model has been developed that includes the most relevant characteristics of the set-up and this model can be used to estimate the field generation, propagation and detection. The model description is used to further optimize the set-up and to estimate minimum energy demand for signal transmission. For the transmission experiments in the HADES URL, the strong background noise at the Mol site was identified as a serious limitation to the possibilities of testing and demonstrating signal transmission using lower signal strength (Fig. 3). However, additional experiments were performed in the Netherlands to demonstrate the principal capabilities of the technique at very low signal strength.

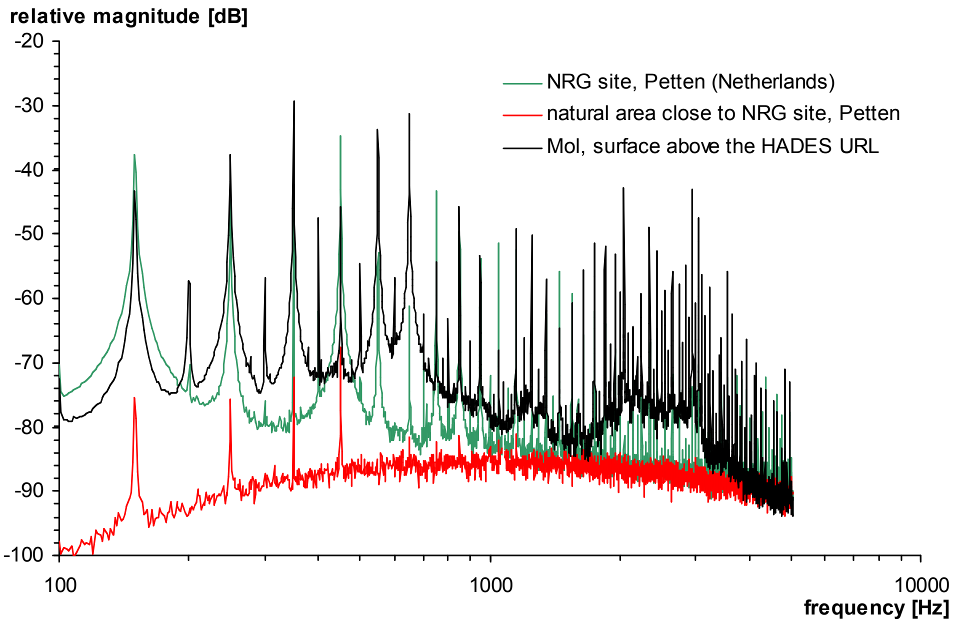

Figure 3: Location specific background noise pattern at Mol, the NRG site in Petten (Netherlands) and a natural area close to Petten

Whereas NRG’s work in 2010 and 2011 was mainly focused on the transmission of signals, in 2012 techniques and methods for enabling the transmission of data will be tested and demonstrated. This includes optimization of the equipment for the small frequency bands identified as optimum transmission channels; and the testing of different modulation techniques in order to optimize energy use. The outcome of this work should enable NRG to give an overview of the relevant features and technological options for transmission of data over long distances through geological media and to provide an estimation of the necessary energy per bit of transmitted data.

For the final part of the programme, the bidirectional transmission of data may be demonstrated. This activity is optional and depends on the results obtained and if time and budget permit. A bidirectional data transmission system may be tested that enables interactive communication with the underground monitoring infrastructure (“talking with the repository”). This could facilitate both, a more efficient use of energy and the option to use and maintain the monitoring infrastructure more flexibly.

DISPOSAL CELL MONITORING SYSTEMS

The French disposal concept for high level, vitrified waste provides for horizontal, steel lined, small diameter disposal cells, as illustrated in Figure 5 below. Some of these disposal cells may be subject to in-situ monitoring during construction, operation, and the initial closure steps, to support the basis for long term safety and to support pre-closure management.

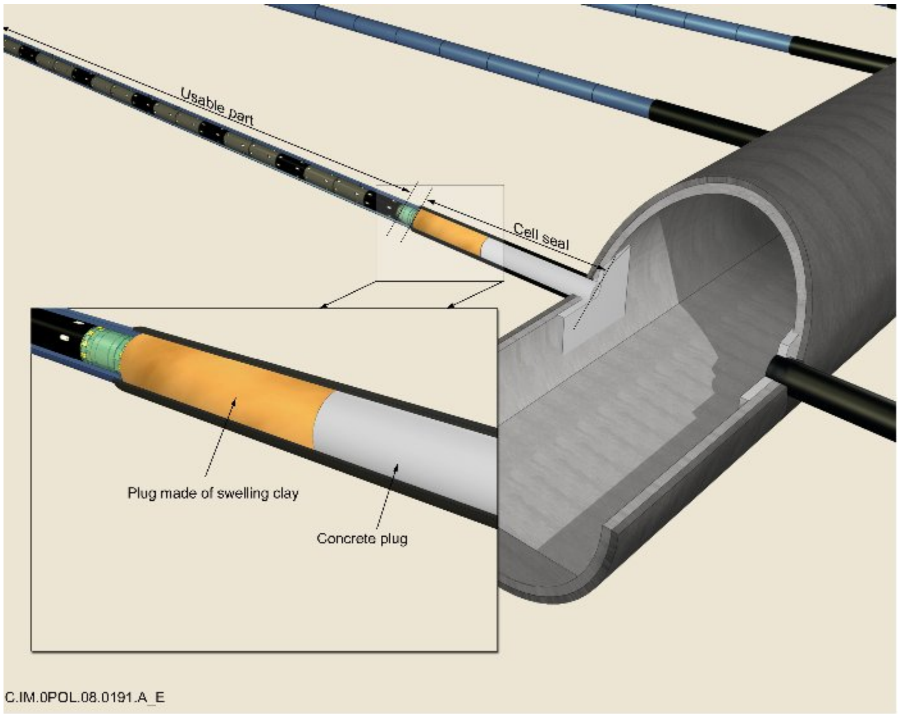

Figure 4: Vitrified waste disposal cell concept

Instrumentation of disposal cells is faced with several challenges. The construction procedure for such a small diameter (~700 mm), horizontal tunnel requires emplacing a steel liner while:

- minimizing the initial void space between cell liner and excavated host rock,
- maintaining friction forces between the heterogeneous rock surface and steel liner sufficiently small for emplacement, and
- limiting damage to the surrounding host rock to preserve its favorable properties.

This presents 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.

The overarching objective of this is to evaluate the feasibility of hydro-mechanical monitoring, as might be used for in-situ 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.

To this end, 4 sections along the cell axis were instrumented, each section comprising:

- 2 displacement sensors to measure horizontal and vertical convergence
- 1 relative humidity sensor inside the gap between liner and near-field
- 3 water pressure sensors inside the gap

- 24 deformation gauges, of which 6 are on the outside liner surface

The deformation gauges on the outside are installed in reservations, protecting them from construction damage with a cover plate (Figure 6). The overall functioning of the deformation sensors was tested and calibrated in surface, axial and radial loading tests.

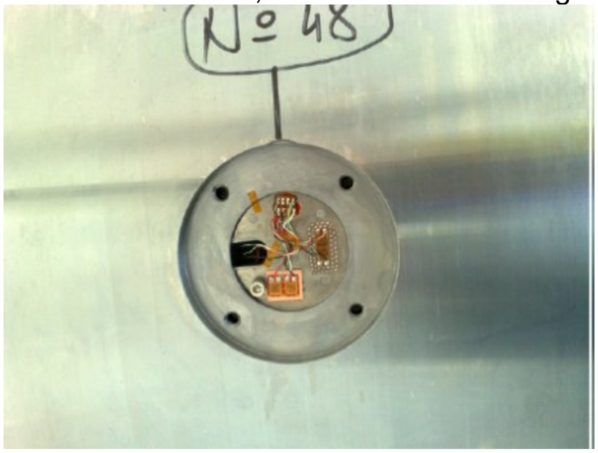

Figure 5: Reservation and installation of strain gauges on outer surface

In addition, fibre optic sensor (FOS) instrumentation is emplaced along an axis of the cell:
- One FOS to measure deformations (Brillouin) on the outside liner surface
- One FOS for combined deformation (Brillouin) and temperature (Raman) measurement on the inside surface
- One FOS for temperature (Brillouin) measurement on the inside surface

The Brillouin sensing on the outside liner is not expected to detect the very small deformations. Rather, it provides the potential to detect localized loading of the liner by the host rock. This 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 modeling from cell liner deformation – as measured by strain gages – to actual rock to liner loading.

The near field was equipped with hydraulic pressure sensors emplaced in boreholes running subparallel to the disposal cell demonstrator. These were emplaced in November 2010, prior to cell construction. These sensors allow monitoring the hydraulic response of the near field to cell construction. An initial pressure peak was expected and observed due to cell construction, 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 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.

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

DISCUSSIONS

The current demonstration programmes are still progressing and the results of these will be reported later. The progress on these programmes is summarised below:

- **Seismic Tomography**: Changes within the disposal cell are expected to produce only very subtle changes of the seismic waveforms. Therefore, highly accurate and repeatable measurements [6] need to be performed.
- **High Frequency Wireless Transmission**: Two key issues can be addressed as regards underground wireless monitoring: transmission distance and energy management: the wireless nodes have been developed to individually negotiate distances of several metres through the usual materials found both in natural and engineered barriers, namely rock, bentonite, mixtures of sand/bentonite, etc. In addition, nodes can be configured as pathways for data coming from other nodes, so networks can be configured to transmit data from distant nodes up to reach the Data Acquisition System. As regards energy management, the firmware developed maintains the nodes in a hibernation, very low consumption mode most of the time, except during the short transmission times. This high energy saving allows for an operative lifetime of several years, depending on the data rate, which is re-configurable at any time. Additionally, some energy harvesting techniques have been considered and tested in laboratory, from which temperature gradient seems to be the most promising one, although still requires further testing to assess its actual effectiveness on this kind of application.
- **Fibre-optic Sensing**: HADES The application of fibre optic sensor technology has confirmed some of the advantages, while it also has shown that sensor technology is much more than just the introduction of a measurement principle. Fibre optic technology in a repository environment requires a protected fibre, reliable connectors, and robust read-out equipment.
- **Wireless Data Transmission**: In line with expectations due to the high electrical conductivity of the subsurface, a strong attenuation of high frequencies appears, that limited the available bandwidth for data transmission to less than 2 kHz. Based on the data gained in the previous steps, optimum frequencies for the signal transmission have been derived on basis of the background noise and the signal attenuation measurements.
- **Disposal Cell Monitoring Systems**: The surface tests have indicated that the installed sensors work in principle. From the 96 installed strain gauges, 7 appear to have failed during installation, while others provide data that needs to be analyzed. The near-field pressure sensor provides data on near-field mechanical response (pressure increase) that is consistent with prior expectations. The relative humidity sensors inside the gap between liner and near-field all appear to function. They indicate a gradual increase of relative humidity towards 100%, suggesting that the near-field is slowly resaturating. The fibre optic sensor installed on the outside surface of the liner appears to have been damaged during construction and checks are being conducted to determine whether measurements can still be performed on part of the cable.

CONCLUSION

The *Technology* programme within the MoDeRn project will help to provide an up-to-date position on monitoring systems focused on disposal cell monitoring. The identification of technical requirements for monitoring has recognised that, in many of the national programmes, definitive programmes have not been determined and may not be appropriate at this stage. The need for appropriate modification and development of monitoring programmes is recognised particularly as designs develop and specific requirements are identified.

The review of the state-of-the-art and in particular with reference to wider industrial practice and the valued exchanges at the Troyes workshop has helped the MoDeRn partners to recognise synergies, to track progress and potentially share developments with these industries. This review also helped to endorse the fact that the research, development and *in situ* demonstrations being conducted within the MoDeRn project reflect leading edge technology.

The main component of the technical programme of trialing and demonstration of these monitoring systems in a range of disposal cell mock-ups in underground research facilities will help the MoDeRn partners to improve their understanding of these systems and support the design and development of future monitoring systems and disposal.

The MoDeRn partners have sought within this programme to engage with a wide range of experts and other stakeholders to gain from their feedback and where feasible to incorporate that feedback within our current programme. Included within the programme are plans to engage with public stakeholders through both discussions on the overall programme and to view first hand some of the underground demonstrators – the details of this engagement are addressed in more detail in a paper to be presented at WM 12 [[7]].

The aim for this programme of work is to advance the capabilities for monitoring and to enhance wider understanding of monitoring technology for disposal systems. A final conference to report the outputs for the MoDeRn programme, sponsored by the EC, OECD NEA and the MoDeRn partners, is planned for spring 2012.

REFERENCES

[1] WM 12 Paper No 12040, *"Monitoring Developments for Safe Repository Operation and staged Closure" (MoDeRn) Project: Project Overview*, Mayer et al, February 2012
[2] WM 12 Paper No 12044, "*Development of a theoretical monitoring system design for a HLW repository based on the „MoDeRn Monitoring Workflow (A Case Study)*", Jobmann et al, February 2012-
[3] EC MoDeRn Project D 3.1.1, "*Site Plans and Monitoring Programmes Report*", August 2010
[4] EC MoDeRn Project D.2.1.1, "*MoDeRn Technical Requirements*", January 2011
[5] EC MoDeRn Project D.2.2.1, "*Monitoring Technologies Workshop Report 7-8 June 2010 – Troyes (France)*", White et all, October 2010
[6] Marelli S., E Manukyan, H.R. Maurer, S.A. Greenhalgh and A.G Green (2010). Appraisal of waveform repeatability and reliability for cross-hole and hole-to-tunnel seismic monitoring of radioactive waste repositories, Geophysics, 75(5), Q21-Q34
[7] WM 12 Paper No 12229, "*Repository monitoring as a socio-technical activity*", Bergmans et al, February 2012.