Monitoring During the Staged Implementation of Geological Disposal:

Technology Summary Report

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RE	Restricted to a group specified by the partners of the MoDeRn project	
CO	Confidential, only for MoDeRn partners	

Table of Content

List of Acronyms

AE	Acoustic Emissions
BER	Bit Error Rate
CRInSAR	Corner Reflector Interferometric Synthetic-aperture Radar
DAS	Data Acquisition System
DIC	Digital Image Correlation
DMS	Data Management System
EBS:	Engineered Barrier System
EC:	European Commission
EDZ:	Excavation Disturbed Zone
EU:	European Union
EURATOM:	European Atomic Energy Community
FP7:	Seventh European Community Framework Programme
FOS:	Fibre Optic Sensing
GTS:	Grimsel Test Site, Switzerland
HADES:	High-Activity Disposal Experimental Site at Mol, Belgium
HFW:	High Frequency Wireless
HLW:	High-level Waste
IAEA:	International Atomic Energy Agency
ICRP:	International Commission on Radiological Protection
ILW:	Intermediate-level Waste
LED:	Light-Emitting Diode
LLW:	Low-level Waste
MoDeRn:	EU-FP7 project "Monitoring Developments for Safe Repository Operation and Staged Closure"
MS:	Microseismicity
R&D:	Research and Development

RD&D:	Research Development and Demonstration
RTD:	Research and Technological Development
SNR:	Signal Noise Ratio
TBM:	Tunnel Boring Machine
TDR:	Time Domain Reflectometry
TDZ:	Thermally Distributed Zone
URF/URL:	Underground Research Facility/Laboratory
WDP:	Waste Disposal Package
WMO:	Waste Management Organisations
WP:	Work Package
WSN:	Wireless Sensor Networks

Glossary

This glossary provides definitions of terms that are used within this report and which are either specific to monitoring or have a specific meaning/definition within the MoDeRn Project.

Disposal Cell: The excavation in which waste is emplaced for disposal including any buffers and barriers (seals or plugs).

Disposal Unit/Disposal Area: A location or area, where a number of disposal cells are located, but separated from other units by accessways

Engineered Barrier System (EBS): The man-made components of the repository, typically comprising the wasteform, the waste container, the buffer, the backfill, and the plugs and seals.

Far field: The rock mass and surrounding geology but distant from the excavation as distinct from *near field*.

MoDeRn Reference Framework: An approach to developing a comprehensive monitoring programme by describing feasible monitoring activities, highlighting remaining technological obstacles, illustrating the possible uses of monitoring results and suggesting ways to involve stakeholders in the development and implementation of a monitoring programme

Near-field: The area of rock mass immediately surrounding and disturbed by the repository excavation in which disposal cells are located.

Non-intrusive Monitoring: Monitoring techniques that allow the transmission of data wirelessly across barriers to avoid or at least minimise the risk of barriers being disturbed by cables.

Pilot Facility: An area of an underground repository used to emplace and monitor a small but representative fraction of the waste in an early stage, i.e. prior to the disposal of the mayor part of waste. The waste in the pilot facility would be retrieved following operation of the facility and would be disposed of in the main repository.

Parameters: Numerical indicators of properties related to processes and events.

Processes: On-going chemical and physical changes in a system.

Stakeholder: An actor with an interest in repository monitoring. Can include, but is not limited to, members of a WMO, regulatory organisations, advisory bodies, and members of the public and/or their representative bodies.

Technical baseline: The level of technical development or the maturity of a specific technology at that time.

Trigger Values: Pre-defined values for monitoring results, which if reached would invoke further action.

List of MoDeRn Project Partners

All the partners in the MoDeRn Project are listed below. In the remainder of this report each partner is referred to as indicated:

Aitemin: Association for Research and Industrial Development of Natural Resources, Spain.

ANDRA: L'Agence nationale pour la gestion des déchets radioactifs, France.

DBE TECHNOLOGY: DBE TECHNOLOGY GmbH, Germany.

Enresa: La Empresa Nacional de Residuos Radiactivos, Spain.

ETH Zurich: ETH Zurich, Switzerland.

Euridice: European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment, Belgium.

Galson Sciences: Galson Sciences Limited, United Kingdom.

Nagra: Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Switzerland.

NDA: Nuclear Decommissioning Authority, United Kingdom.

NRG: Nuclear Research and consultancy Group, The Netherlands.

Posiva: Posiva Oy, Finland.

RAWRA (now SURAO): The Radioactive Waste Repository Authority, Czech Republic.

RWMC: Radioactive Waste Management Funding and Research Centre, Japan.

Sandia: Sandia National Laboratories, United States.

SKB: Svensk Kärnbränslehantering AB, Sweden.

University of Antwerp: University of Antwerp, Belgium.

University of East Anglia: University of East Anglia, United Kingdom.

University of Gothenburg: University of Gothenburg, Sweden.

1 Introduction

The main goal of the collaborative, European Commission 7th Framework MoDeRn Project (**Mo**nitoring **De**velopments for safe **R**epository operation a**n**d staged closure) project 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 during a staged approach to disposal of radioactive wastes. To achieve this goal, 18 partners representing 12 countries and including 8 national radioactive waste management organizations have been working collaboratively within this EC project since 2009. The MoDeRn Project work programme addresses: *Process* (why monitor, developing a monitoring programmes, translating monitoring objectives into practice and using the results from monitoring) (MoDeRn, 2013a); *Technology* (technical requirements and constraints, state-of-the-art for monitoring technology, focused R&D and the development of techniques through demonstrations in underground research laboratories (URLs)) (this report) ; and *Case Studies*, where examples have been applied to current disposal concept designs in three host rock types (MoDeRn, 2013b).

1.1 Target audience for this report

The target audience for this report is assumed to have a good understanding of radioactive waste management. The report has been developed predominantly by representatives of WMOs and monitoring experts. It is written to provide a high-level overview, to WMOs and other interested stakeholders, of the status of monitoring technology, primarily focused on *in situ* repository monitoring. The report references a number of more detailed reports on the research and demonstration work conducted under the MoDeRn project. It also provides information on the scope and current limitations of these monitoring techniques which could assist in discussions on the approach to monitoring with a range of stakeholders.

The project recognizes that all stakeholders to a repository programme are also likely to be interested in or have a specific role to play with respect to the development, implementation, and use of monitoring. Therefore the content of this report is intended to be informative to all stakeholders, including:

- Safety Authorities likely to supervise the monitoring approach and to impose some monitoring as license condition;
- Designated Advisory Boards likely to inform national decision makers on waste management issues;
- The local public and/or their representative bodies likely to take a particular interest in monitoring to verify that protection goals are met.

1.2 Background to the MoDeRn Project and this report

The MoDeRn project aims to provide implementing organisations and other interested parties with a *reference framework* for the development and possible implementation of monitoring activities and provide a basis for stakeholder engagement during relevant phases of the radioactive waste disposal process i.e. during site identification, site characterisation, construction, operation and staged closure, as well as post-closure institutional control. 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 provides information on barrier performance and early evolution of the disposal system design. 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.

MoDeRn focuses particularly on monitoring *in situ* repository system behaviour, as from a technical point of view this remains the biggest challenge today, one that is relatively unique to geological disposal. Other types of monitoring activity that will be called for in any geological disposal programme, such as operational safety, environmental and safeguards monitoring, are likely to be similar to those already in use at other nuclear installations and their implementation can be planned and further developed based on prior experience. As they are not confronted with the same series of challenges towards their implementation, they were not considered explicitly within MoDeRn.

As part of the MoDeRn project, previous (national and international) work addressing monitoring objectives has been reviewed and elaborated to better reflect the actual implementation of disposal monitoring activities, taking into account a variety of physical and societal contexts, available technology, and feedback from both expert and non-expert stakeholder interactions, obtained through dedicated workshops, and focussed social sciences research activity (MoDeRn, 2013c).

The partners, in developing this programme, recognised the significance of specific national contexts in defining monitoring requirements and the need for flexibility within the framework to capably address these requirements. The MoDeRn programme has also included engagement with both experts and public stakeholders to provide a wider perspective on monitoring and the ultimate purpose of the MoDeRn project is to utilise the outputs from this work as a basis for consultation on and development of monitoring programmes with stakeholders.

A separate *Framework* report (MoDeRn, 2013a) has been produced to address the processes that need to be applied for the implementation of a realistic monitoring programme. The *Framework* report sets out a systematic approach for the development of a competent monitoring programme which provides a basis for communicating with stakeholders and providing a means to address their expectations (objectives). This framework provides a structured approach for assessing how those objectives can be addressed, including the process for assessing and applying monitoring technologies that can be implemented in a repository context (feasibility). It then considers how objectives can be met by setting out, as examples, a number of *case studies* applying monitoring in 3 geological environments (granite, clay, salt). The approach to these *case studies* is summarised within the Framework Report but has also been developed and reported in more detail in a separate report (MoDeRn, 2013b).

The output from the MoDeRn project is 18 published reports as illustrated in Figure 1-1 below. This Technology Summary Report was developed as a summary of the significant programme of these MoDeRn research, development of monitoring systems and components, and demonstration activities to help those parties interested in applying monitoring technology to gain an overview of the technology programme and to understand the potential applications for those technologies addressed in the more detailed and specific technical reports listed under WP2 and WP3 reports (see Figure 1-1). These more detailed reports allow technical specialist and those interested in applying a specific technology to access the greater level of technical information provided. The aim in pursuing this work is to understand the capabilities of monitoring systems. This would enable future research, development and demonstration to focus on specific technology studies to address any weaknesses in, and to enhance the performance of, monitoring systems. These full-scale demonstrations also help in the thorough testing (and development through learning) of both of the disposal design and the monitoring systems prior to use in a repository.

The Technology Summary Report aims to establish: what is required from monitoring; what monitoring techniques are available; and what techniques could be developed and improved to best address requirements.

Figure 1-1: MoDeRn Project Reports

In the MoDeRn project five research, development and demonstration activities have been progressed with the developed systems being assessed in practice by installing and testing them under realistic conditions in three European underground research facilities (Hades URL, Grimsel GTS and Bure URL.

These MoDeRn programmes for developing and demonstrating monitoring systems in URLs will help the development of geological disposal programmes by:

- Advancing understanding of the capabilities (and limitations) of the monitoring systems being developed and tested;
- Providing implementers with information on the performance and early evolution of the repository design which can assist, through design development, in optimising the performance and efficiency of planned repositories;

- Providing information to support decisions on whether to advance to the next stage of a stepwise disposal process;
- Discussing and sharing of these programmes with stakeholders to enable better understanding of the monitoring disposal cell designs and the performance of those designs;
- Assisting further RD&D programmes to focus on technical areas where development needs have been identified;

Although many national programmes for geological disposal are at the early stages, where in many cases, neither sites nor the geological environment for disposal have yet been identified, the partner organisations recognise the need to assess, develop and refine available techniques at this stage. The MoDeRn partners recognise that it is necessary in the early stages of such development to pursue cautious and more intensive monitoring programmes until analyses of the results from monitoring can be used to inform appropriate monitoring programmes going forward. The partners also recognise the limitations to providing monitoring systems capable of functioning across the timescales for long-term safety cases, nonetheless, development of systems capable of monitoring the early stages of evolution will help to provide information to support decisions on whether to progress to the next stage of a stepwise process. 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 development of mock-ups of geological disposal and the monitoring of these can help both in the understanding of early evolution and in the development of disposal designs.

1.3 Structure of the report

Section 2 of this report summarises the key drivers and objectives for the MoDeRn technology programme which, taking account of specific national contexts, will influence specific national programmes. It sets out some of the emphasis that the MoDeRn partners have placed on monitoring systems and how this has influenced the specific focus of the research, development and demonstration (e.g. the non-intrusive or wireless techniques, robustness, reliability and durability). It describes the key objectives of understanding the current state-of-the-art and how these have been addressed within the programme, taking account of experience in related industries and consulting with expert stakeholders, as well as gaining some understanding of what the public might want from monitoring programmes.

Section 3 takes account of the technical requirements from monitoring across various national programmes recognising that these programmes are at different stages ranging from: operating facilities and safety case submission, through to those programmes where sites or specific host rock types have not yet been identified.

Section 4 summaries the work within the MoDeRn programme to evaluate the current state-of-the-art including workshops arranged with monitoring specialists from wider but related industries (oil, gas, mining and civil construction).

Section 5 describes the key technical activities within the MoDeRn programme summarising the research and development of 5 monitoring systems and their testing and demonstration at mock-up disposals in underground research laboratories (URL) at Bure in France (indurated clay), Grimsel Test Site (GTS) in Switzerland (granite) and in HADES in Belgium (plastic clay). These include:

- Seismic tomography at the GTS

- High frequency wireless sensor networks (Also called short range wireless data transmission) at GTS
- Fibre optic sensing and acoustic emission at HADES URL
- Long range wireless data transmission at HADES URL
- Testing of disposal cell monitoring systems at Bure URL

Each of these work programmes is described in more detail in 5 individual reports (MoDeRn 2013, d, e, f, g , h and n).

Section 6 provides the main conclusions arising from this technical work programme and identifies: the key values from the research, development and demonstration activities; lessons learned; and areas for future development. This also provides indications on the likely feasibility of implementing the techniques evaluated and identifies options to address knowledge gaps and technology limitations.

2 Objectives of this report

The objectives of the MoDeRn Project technology programme are to provide an up-to-date position on the technical requirements and constraints for monitoring of geological disposal and to understand and develop the state-of-the-art for monitoring technology through focused R&D and the development of techniques through demonstrations under realistic conditions in underground research laboratories (URLs). Monitoring is a necessary and regular part of everyday construction, operational and environmental management activities, mainly to provide information about safety and the environment by checking that the design is performing within expectations. Many monitoring techniques have been used successfully in a wide range of applications to address the purposes above and these practices would be applied as a matter of routine in the construction, operation and closure of a geological disposal facility.

As stated in Chapter 1, the focus for research, development and demonstration within the MoDeRn project is on *in situ* repository monitoring. The ability to monitor after closure is important to many stakeholders and merits further consideration in future work programmes. Some consideration has been given in the MoDeRn programme to what techniques could be applied to monitoring post-closure.

The challenge for geological disposal is to be able to provide monitoring information on the evolution of a disposal cell and safety relevant barrier systems after the waste has been isolated behind the purpose-designed barriers. It is particularly important that any monitoring system does not compromise the passive safety of the barriers, which form an integral part of the disposal cell design. This aspect is clearly stated in the IAEA Safety Standard (IAEA, 2006):

"*Monitoring programmes will be designed and implemented so as not to reduce the overall level of post closure safety*"

To address this objective of not reducing the overall level of post-closure safety, any monitoring of the performance of multiple barriers should consider the possibility of applying non-intrusive monitoring techniques. Non-intrusive monitoring techniques or techniques that allow the transmission of monitoring data wirelessly across barriers avoid or at least minimise the risk of the barrier being disturbed by cables. Consideration also needs to be given to the problems associated with the failure of monitoring sensors located within the barrier where these could not be repaired or replaced without disturbing the engineered barriers. It is also important that any monitoring systems installed are robust to the harsh environment (heat, humidity, radiation, pressure and chemical interaction) for the disposal of higher activity wastes and spent fuel.

One of the objectives of the technical part of the MoDeRn research programme is to understand and document monitoring technology which can be applied to geological disposal monitoring by reviewing and recording what is available both within geological disposal and in similar industrial applications. This wider view and consultation with other industries includes an international workshop in the early stages of the project and the findings are summarised in Section 4.

The monitoring RTD and demonstration work performed in MoDeRn is described in Section 5. One focus of these studies is in developing applicable state-of-the-art technologies in realistic situations in mock-up disposal cell in underground research facilities in order to replicate environments similar to that for actual disposal. This considers factors such as heat, humidity and pressure. From the results of these studies, the capabilities and limitations of particular systems and techniques are evaluated. Subject to the evaluation, improvements to performance and reliability can either be made during the project, if practicable, or be recommended as part of any future development or use.

It is important to minimise disturbance to the barrier systems, wherever possible, therefore the second focus of the demonstration activities within the MoDeRn project has been to further the potential for applying non-intrusive and wireless techniques and researching and developing these techniques to improve their effectiveness for specific applications. The monitoring research, development and demonstration, described in Section 5, are focused on applying techniques which are advancing the state-of-the-art and includes non-intrusive and wireless techniques as well as installing monitoring systems in challenging physical conditions, where designs are focused on avoiding damage to monitoring systems.

The intent within the technology programme is to deliver "best value for money" and in all of the demonstrator projects these have been built upon existing infrastructure or will be attached to infrastructure which is being developed and financed outside of the project. In most cases where mock-up facilities are developed the provision of a monitoring system would be an essential part of the information sought from such facilities, therefore utilising and developing state-of-the-art techniques (in some cases alongside more conventional techniques) provides additional benefits.

When developing novel or innovative monitoring techniques, particularly where those techniques require interpretation or validation of results, there are benefits in assuring confidence in the analysis by utilising already proven techniques alongside the novel technique, as a means of validating the more novel technique and providing direct comparison with already well-developed techniques. This provides valued learning about the technique with increased confidence in and understanding of the data/information provided. Central to the acceptance of any proposed monitoring system will be data quality assurance, data and records management.

The experience and results from the MoDeRn work can help to determine where there is value in further development to support future monitoring programmes. It is recognised that the monitoring installations in most cases will remain available after the completion of the MoDeRn project and these can be utilised to provide further monitoring information, including the lifetime, durability and accuracy of the systems over a more extended time period than the duration of this project.

The development of monitoring technology within the MoDeRn project will provide a better basis for implementing organisations, in particular, to communicate more specifically about capabilities and limitations of monitoring techniques with regulators, public stakeholders and monitoring specialists in order to advance the transparency of monitoring programmes. Feedback from such dialogue should help to define future monitoring programmes and help improve an understanding of monitoring programmes and potentially improve acceptability of geological disposal.

As part of the social science programme within MoDeRn a series of engagements were held with public stakeholders to discuss monitoring and the MoDeRn project. This engagement included a field trip by Belgian, Swedish and UK stakeholders to the GTS and Mont Terri sites to view monitoring work and other URL research. A report on these engagements has been published on the MoDeRn website (MoDeRn 2013i).

The specific objectives and rationale for each of the 5 research, development and demonstration programmes within the MoDeRn project are described for each project in Section 5.

3 Technical Requirements

In the early stages of the MoDeRn project, a Technical requirements report (MoDeRn, 2013j) was prepared to provide an overview of what was likely to be required when developing and implementing a monitoring programme for geological disposal of radioactive waste. The examples of technical requirements were expressed for three host rock types (salt, granite & clay). It is noted that "technical requirements" are not to be understood in the sense of "mandatory - obligation to implement", but in the sense of "specifications that need to be addressed" when selecting monitoring technology best suited to respond to technical monitoring objectives.

The report provides an initial overview and cannot be considered definitive as this would require all available details on repository design, safety strategy, and selection of precise emplacement of sensors, etc., to be defined – this is not possible at this stage as many programmes have not yet identified either a site or a host geology. The results obtained from a monitoring programme will provide information for decision makers to enable them to determine the scope, frequency and any additional needs from the future monitoring programme. The EC Thematic Network Report (EC, 2004) also points out:

"*The extent and nature of monitoring will change throughout the various stages of repository development, and monitoring plans drawn up at an early stage of a programme will need to reflect this. It may also be expected that the plans will be revised periodically in response to technological developments in monitoring equipment, modifications to the repository design and changing societal demands for information*."

This early identification of technical requirements does, however, provide a good working basis to gain an appreciation of the range of technological specifications for monitoring systems in a repository.

This will enable evaluation of those available technologies which are likely to respond to the needs of repository monitoring; where specific adaptations of available technologies (e.g. to enhance resistance to environmental conditions) are needed; and where improvements or entirely new developments are necessary (e.g. to monitor without the risk of degrading performances of engineered barriers).

3.1 Basis of a monitoring programme

A monitoring system to be applied in a potential monitoring programme will be composed in general of the following main components/equipment:

- Sensors that transform physical or chemical properties into analogue signals;
- Data transmission media between different parts of the monitoring system, usually composed of cables, amplifiers, filters, signal converters (that transform sensor signals into digital data), hubs and other electronic devices including wireless data transmission units;
- Data management systems (DMS) to register, (pre)process, store and display the digital data from the converters;
- Power supply system to power up all the equipment;

There are several technical or operational requirements placed on a monitoring programme, summarised as requirements to:

- Address individual national programmes and disposal concepts and the specific nature of the parameter to be measured;
- Ensure safety functions are not impaired;
- Address sensitivity (including to other environmental variables, limitation on placement and interference from other systems), precision and range of values to be measured;
- Provide redundancy, ability to detect defective sensors and erroneous results, limiting the loss in the case of failure;
- Address durability and long-term stability of the monitoring system in unfavourable environmental systems without access for maintenance/calibration.

The environmental conditions in a repository are likely to be more aggressive to monitoring equipment (sensors, data loggers etc.) than in other applications, and are likely to exceed the conditions for which monitoring equipment has been designed. This necessitates the development of specialised equipment to meet extremes in temperature, mechanical pressure, hydraulic pressure, water saturation, salinity, radiation and displacement.

Furthermore, as the rate of transient processes occurring in the near field is expected to be slow, and because there is a requirement that monitoring should not compromise the passively safe design (IAEA, 2001), additional considerations need to be addressed in developing a monitoring programme, especially when the monitoring is concerned with near field monitoring after the emplacement of waste and engineered barriers. These include developing compromises between access (boreholes, etc.) for data transfer and energy supply, versus the challenges of providing in situ power over long periods, for example to allow remote monitoring and wireless transmission of monitoring data. When considering the long timescales involved in monitoring, issues like drift of measuring devices and the need for calibration, reliability/longevity and the possibility for repair or replacement (without creating undue disturbances) are relevant aspects that must be considered in designing repository monitoring schemes.

Requirements on monitoring systems could, however, be less restrictive within a pilot facility compared with a disposal facility but monitoring system design and accessibility to monitoring components will still need to take account of and address the requirements of the mock-up being monitored. Examples of this could be the use of cables instead of, or as well as, wireless technology and valuable additional information, such as corrosion or mechanical performance, can be determined by dismantling a mock-up after completion of a demonstration.

The following parameters for monitoring have been identified as being of likely interest in various international repository monitoring programmes: temperature, mechanical pressure, hydraulic pressure, water content/saturation, salinity, radiation, displacement, deformation, humidity, gas concentration (oxygen, carbon dioxide, hydrogen and methane), gas pressure, pH, Eh, concentration of colloidal particles and alkalinity. However, given that the geological environment and disposal concepts envisaged for disposal of radioactive waste are not known in all cases there may be specific technical requirements on the capabilities of monitoring technologies that must be addressed before successful repository monitoring can be undertaken.

The following areas for potential monitoring were identified (Figure 3.1):

- Waste package and buffer (a specific buffer does not exist in some concepts or it is substituted by overpacks and liners);
- Near-field rock (and, if included in specific designs, structural elements of disposal cells and repository infrastructure such as shafts, ramps, tunnels);

- Backfill;
- Seals; and
- Far-field rock.

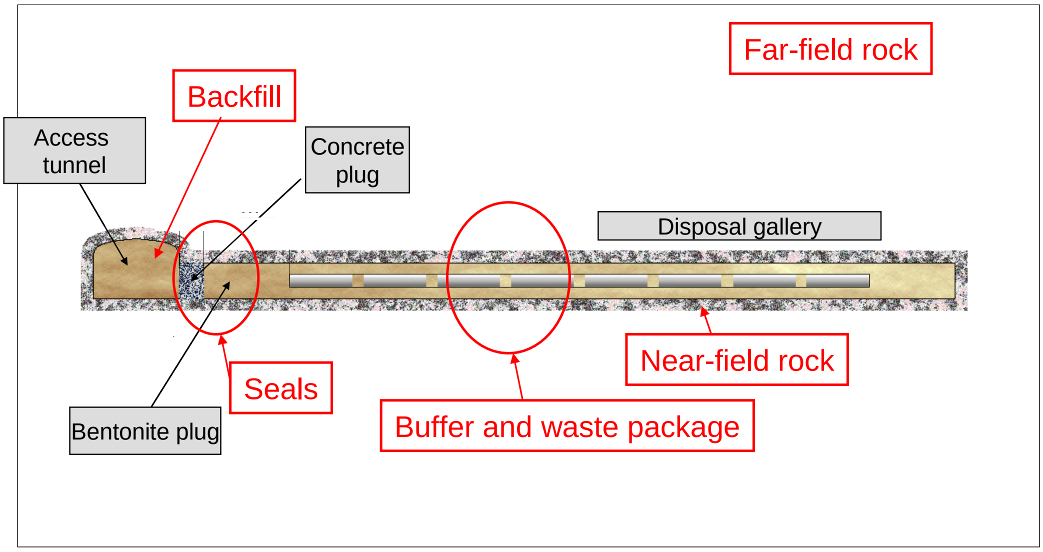

Figure 3.1: Schematic of potential monitoring areas

4 State-of-the-art

The objective of MoDeRn WP 2.2 was to establish the state-of-the-art of applicable monitoring technologies which could be applied to repository monitoring programmes to allow a comparison of the potential monitoring needs with the available options and techniques thus highlighting gaps in knowledge or application of monitoring techniques that still need to be addressed.

Such state-of-the-art was established based on experience in comparable monitoring environments, including URLs (Underground Research Laboratories), surface-based ILW (Intermediate Level Waste) repositories and long term storage experiences, as well as relevant industrial experience in other fields, for instance, nuclear power plants, mining operations, subsurface infrastructures, hydrocarbon exploration or CO_2 sequestration.

4.1 Monitoring Technologies Workshop

MoDeRn partners recognised the value of assessing monitoring applications in technical fields outside of geological disposal and, at an early stage in the project programme, brought together monitoring specialists from a range of disciplines to present and discuss their work and experiences in applying state-of-the-art techniques to monitoring in their specific applications. 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.

A report on the workshop (MoDeRn 2010a) is available on the MoDeRn website. Set out below are a number of the key areas of monitoring development relative to geological disposal.

Wireless sensor networks (WSNs) find application in many industrial and civilian areas, including industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control. Transmission is generally considered through-air, with a lesser or greater ability to transmit through obstacles. Developments in WSNs and through-the-earth data transmission are of interest to repository monitoring as these technologies may support the transmission of monitoring data from the near-field of the repository system without affecting the passive safety of the EBS. Current battery power limitations restrict the operation of WSNs to 1-2 years. However, data processing techniques can reduce the quantity of data requiring transmission by 99%, which may lead to increasing effective operating time to 10 years (See Section 5.2 for most recent developments within MoDeRn).

Wireless through-the-earth transmission: At the Troyes workshop, first results on MoDeRn RTD on long-distance wireless data transmission were presented (see for more details Section 5.4).

A fibre optic sensor is a sensor that uses an optical fibre either as the sensing element (intrinsic sensors), or as a means of relaying signals from a remote sensor to the electronics that process the signals (extrinsic sensors) (Measures, 2001; Yin et al., 2008). A laser is currently used as the light source for all commercially available fibre optic sensors. Lasers have a relatively high power consumption compared to other light sources (e.g. light-emitting diodes). Optical fibres have a wide range of potential applications because they can operate under harsh environments, including environments with strong electromagnetic fields, high temperatures, explosive potential, aggressive chemical species or ionising radiation. Fibre optics have found particular application in civil engineering applications, where glass optical fibres can measure strains of 1%, and where polymer optical fibres have been demonstrated to measure strains up to 20% and can potentially measure strains up to 40%. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near-field. Fibre optic sensors provide distributed monitoring and, as such would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.

Seismic interferometery uses cross-correlation techniques to map the velocity structure of the sub-surface, using background seismic signals (Campillo and Paul, 2002; Snieder, 2004; Snieder, 2006; Wapenaar and Fokkema, 2005). Changes in the velocity structure can be used to develop an understanding of the impact of processes on the physical properties of the sub-surface, and thereby to develop an understanding of the processes themselves. 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%. Seismic interferometery is being developed within the oil and gas industry, but is mainly used in research and academic settings. Future developments could allow monitoring of physical changes in the sub-surface (e.g. gas generation and migration, and increases in temperature), although this would be highly dependent on the geological environment.

Seismic reflection surveys provide information on the velocity structure of the sub-surface by recording the reflection of a known seismic source. Time-lapse three-dimensional (3D) seismics can be used to image the movement of fluids within the earth (European Association of Geoscientists and Engineers, 2003), e.g. a gas plume, and have been used for monitoring CO_2 plumes resulting from carbon sequestration projects. The resolution of time-lapse 3D seismic monitoring is now such that 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 CO2. Seismic reflection could be used to monitor gas generation and migration, although this would be highly dependent on the geological environment and disposal concept.

Acoustic emissions and microseismic (AE/MS) surveys monitor fracturing in rock and man-made materials through measurement of the seismic signals emitted when materials fracture (Young and Martin, 1993). AE/MS monitoring has the potential to monitor the mechanical evolution of the EBS following closure of a disposal cell, prior to closure of the access ways and service areas within a repository (i.e. to be used as part of a staged closure process). 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. (See Section 5.3)

Geotechnical monitoring will be required in geological repositories to determine the physical nature of the rock mass, and the rock mass response to excavation, emplacement of waste and closure of the facility (Bell, 2007). Geotechnical monitoring will contribute to confirming the host rock response to construction and operation, and thus may contribute to the demonstration of operational safety. In terms of the state-of-the-art in geotechnical monitoring recognised at the Troyes Monitoring Technologies Workshop:

- Strain monitoring using extensometers and tell-tales can now monitor millimetre-scale displacements in tunnels.
- Stress monitoring can detect the impact of the excavation on the *in situ* stress up to 100 m from the tunnel.

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.

Surface monitoring using air-based and satellite-based systems can be used to develop an understanding of the changes to the ground as a result of repository development and to monitor for unexpected activity. Satellite-based optical imaging technology is readily available with a 50 cm resolution, and satellite-based corner reflector interferometric synthetic-aperture radar (CRInSAR) provides millimetre-scale monitoring of changes in ground elevation. It was noted that technology such as satellite imagery and radar interferometery could play an important part in aspects of post-closure monitoring and Safeguards surveillance.

4.2 State-of-the-art report

The information from the international workshop coupled with the expertise and research of the MoDeRn partners has been used to compile a report on state-of-the-art on monitoring for geological disposal (MoDeRn 2013k), which identifies available monitoring technologies and advises:

- The context of the monitoring technique(s) discussed and the applicability to repository monitoring practice.
- Source references for further information and previous experiences of applying the technique(s).
- Applicability and limitations of implementing the technique(s)
- Further development of the technique(s) that would be of value to enhance its applicability for repository monitoring.

Emphasis was placed on sensors, signal transmission, local energy sources and signal diagnosis tools and techniques, which will be relevant for monitoring in repositories. Special attention was paid to innovative approaches and therefore to the results of few RTD activities focused on promising monitoring technologies, which were identified from the outset and were also developed within the MoDeRn project (Chapter 5):

- Wireless techniques and adequate power sources;
- Geophysical monitoring techniques based on improved resolution waveform analysis;
- Fibre optic sensors;

The applicable monitoring technologies have been structured in the following sections:

- Repository-based monitoring;
- Borehole-based monitoring;
- Surface-based monitoring; and
- Aerial monitoring systems.

As the main interest of the MoDeRn project is the monitoring to be carried out during the operational and the early post-closure phases, the state-of-the-art report pays more attention in those techniques that are more suitable for that period, which are the repository and borehole-based ones.

The state-of-the-art report reviews the applicable monitoring technologies that could be applied to repository monitoring programmes providing not only specific technical information about the different techniques but also evaluation of the maturity and applicability of the described technologies. This study highlights gaps in knowledge or application of monitoring techniques that still need to be addressed.

The information provided in the document for each relevant parameter is structured in general as follows:

- Why measure? Justification of the need for measuring such parameter within the repository.
- Concepts and definitions (only if required). Concepts and terms used for describing the techniques.
- Techniques and signal characteristics. Description of the main existing techniques, including their advantages and drawbacks.
- Experiences and results. Experience accumulated when using the different techniques in environments similar to a radioactive waste repository.

The state-of-the-art report (MoDeRn 2013k) is available on the MoDeRn website. As an outcome of the state-of-the-art, some areas for further improvement in existing monitoring technologies have been identified, for instance:

- Adequate corrosion sensors are required;
- The available sensors should be tested and if required, shielded against radiation;
- Long-term durability of sensors should be evaluated or improved;
- Additional research is needed regarding long term power supply;
- Combined solution (short-distance high-frequency and long-distance low-frequency) for wireless data transmission should be established.

In MoDeRn WP4.4 (MoDeRn 2013m), the necessity to address long-term data management and signal analysis in developing monitoring systems is discussed, recognising that accurate data acquisition requires a chain of sensors, cables, connectors, analogue-digital-converters, data-acquisition units, data-processing units, correction and calibration methods, and data transmission units all working to specification. The report emphasises that the quality of monitoring data does not only rely on the monitoring devices itself, but also on the proper operation of each of the given components, recognising that it is the monitoring results and not the sensor readings that will be used for decision making, thus statements on quality need to address the whole process of data management and not just sensor performance.

Robust methods and procedures that qualify all aspects of the performance of the applied monitoring systems are essential to allow the data to be used in decision making. Owing to the long timescales and the fact that sensors or other components of the monitoring equipment may be inaccessible, repository monitoring is challenging, and the possibility of failure detection will be an important aspect of the robust methods that need to be developed. Looking at the examples of applied failure detection methods and detection procedures at the different URLs in Europe it is clear that the opportunity for focussed development and application of such methods and procedures over the envisaged timescales for repository operation is currently limited. This is due to the fact that monitoring techniques are generally applied as part of research projects. The experiments performed are often limited in time and thus real long-term monitoring over several decades has not been possible. Under these circumstances, there will always be the possibility to recover the implemented sensors and check for any performance changes or failures, so there is not an absolute need for a fail-safe sensor to be used in the short-term experiments. However, when it comes to the detection of failures, several specific features of monitoring in waste disposal can be used:

- Evolution of parameters is usually slow, enabling efficient criteria to be defined for local failure detection systems.
- Redundancy can be applied easily and on different level:
- Redundant sensors in the same disposal component.
- Sensors at different locations/distances from a disposal component.
- Repetitive monitoring of the same component in different parts of the disposal system.
- Distinct functional redundancy.
- Correlations can be used because in most cases more than one parameter is measured, and these parameters often have a constitutive relationship with each other.

Potential failure modes have been studied as part of the *Case Studies work* within the MoDeRn project (MoDeRn, 2012) and it was concluded that in numerous and widely varying safety-relevant areas, different methods to detect errors and failures have been developed, many of which are applicable to repository monitoring. These vary with respect to the degree of reliability that can be achieved, the technical efforts necessary and the special requirements of the particular application.

The state-of-the-art report demonstrates that there are already many principal candidate techniques available that, however, often need to be developed further for application in future repository monitoring programmes. This is also true for techniques to be applied in the vicinity of the waste, those classified as repository- or borehole-based. A reliable solution that avoids the use of cables is necessary here and further effort should be made to obtain reliable and qualified solutions for the data transmission using wireless techniques. The same applies to fibre-optic sensing (FOS) that will reduce the number of cables due to the ability to multiplex.

A lot of comprehensive information has been compiled within the State-of-the-art Report with the aim of helping implementers and others in the development of future decisions on the design of repository monitoring programmes. Nevertheless, it is recognised that some of the techniques considered are rapidly evolving and therefore users should recognise the need to check for any new developments before considering applying a particular technique.

5 Research, Development and Demonstration on Monitoring

A major component of the MoDeRn technical programme is the testing and demonstration of monitoring in disposal mock-ups in underground research facilities. The use of disposal mock-up provides opportunities for these techniques to be employed in conditions more appropriate to what would be expected in an actual disposal. In each case the programme within MoDeRn has been focused on the development and testing of state-of-the-art monitoring technology as part of a programme of testing and evaluation of different disposal concepts. Utilising these mock-ups for trial and evaluation of monitoring systems has ensured that these programmes have provided value for money, while at the same time providing valuable information on the performance of the disposal mock-up. The provision of these mock-ups in underground research facilities helps provides valuable opportunity to learn more about the disposal process and to support the testing and evaluation of new techniques. Continued monitoring of or the dismantling of these constructions provide a useful basis for consolidating understanding of:

- The likely early evolution of a disposal design;
- The reliability of constructing the barriers to the required design with the potential for optimisation of these designs through learning;
- The robustness of barrier designs and the capacity to construct these efficiently;
- The capacity to monitor the design and the impact of the design and the environment on monitoring systems; and
- The potential to improve the design and installation of monitoring systems.

The five research, development and demonstration programmes within the MoDeRn project address a number of specific objectives are described in more detail in Section 5.1 to 5.5 below. This section provides a high-level summary of the outputs from these studies; for more detail the reader should consult the individual references for each programme which have been published on the MoDeRn website (www.modern-fp7.eu). These are as follows:

- 5.1: Seismic tomography at the Grimsel Test Site (GTS) in Switzerland (MoDeRn, 2013d);
- 5.2: High frequency wireless sensor networks (Also called short range wireless data transmission) at GTS (MoDeRn, 2013e);
- 5.3: Fibre optic sensing and acoustic emission at the HADES URF at Mol in Belgium (MoDeRn, 2013f);
- 5.4: Long distance wireless data transmission at HADES (MoDeRn, 2013g); and
- 5.5: Testing of disposal cell monitoring systems at Bure in France (MoDeRn, 2013h).

5.1 Seismic Tomography

This programme of research, development and in situ testing is aimed at advancing the use of cross-hole and hole-to-tunnel seismic monitoring techniques as a means of non-intrusively monitoring a disposal cell after isolation of the waste. Central to this work is the full waveform analysis. This work (MoDeRn, 2013d and MoDeRn, 2013n) was conducted by ETH Zurich in Switzerland supported by NDA and reflects a continuation of monitoring development initiated under the EC ESDRED project (http://www.esdred.info/). Two PhD studies (Manukyan, E. 2011, Marelli, S. 2011) have been completed which detail the RD&D and analysis of the results.

Controlled source seismic tomography (Marelli, 2012) offers the potential for high-resolution imaging of the EBS. Seismic imaging is based on the fact that any heterogeneity in the elastic properties of the medium (e.g., seismic wave velocity, density and attenuation) affects the wave propagation characteristics, and will cause changes in the waveforms (e.g. travel time, amplitude and phase). Tomographic imaging allows a detailed image of the subsurface elastic properties to be developed based on processing of the characteristics of the seismic signals that have travelled through the medium of interest (Figure 5-1-1).

Travel-time tomography exploits the arrival times of selected seismic phases to create the velocity images, whereas ray-based amplitude tomography uses the maximum amplitudes of the waves to deduce the attenuation characteristics of the medium of interest. In contrast, full waveform inversion techniques exploit the full information content of the seismograms, and consider both the amplitude as well as the phase of the recorded signals.

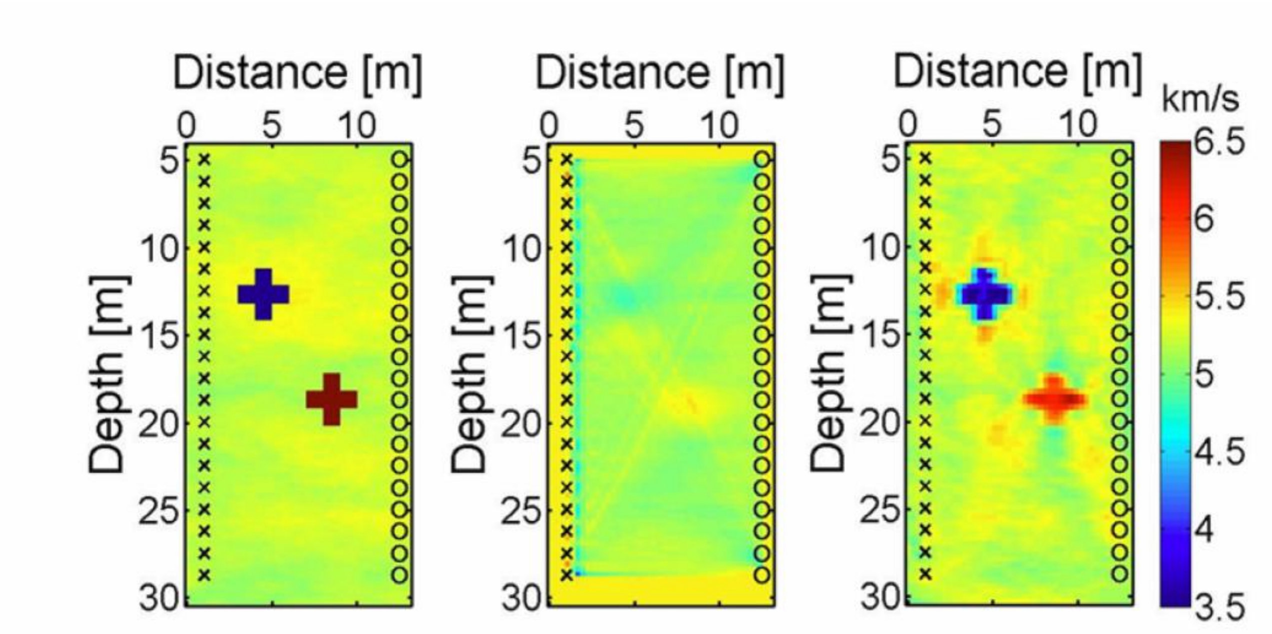

Figure 5-1-1: Three synthetic tomograms illustrating how seismic tomography can be used to image the elastic properties of the sub-surface. The tomograms are 2D plots of seismic velocity and show the locations of the theoretical signal sources (crosses) and receivers (circles). The image on the left is a velocity model in which two anomalies are emplaced, one low-velocity anomaly (in blue) and a high-velocity one (in red). The image in the middle is a tomogram based on travel-time tomography and the image on the right is a tomogram based on full waveform inversion.

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. As the EBS evolves, for example through resaturation, the generation and migration of gas and potentially through displacement the seismic signature will vary. These variations could be detected through seismic tomography. Seismic tomography has, therefore, the potential to support the post-emplacement monitoring of the EBS.

5.1.1 Objectives and rationale

At Grimsel Test Site, an underground research laboratory (URL) excavated in the crystalline rock of the Swiss Alps, cross-hole and hole-to-tunnel seismic methods have been employed as a means of monitoring induced changes in an artificially saturated bentonite wall confined behind a low pH shotcrete plug, constructed as part of the EC ESDRED project (http://www.esdred.info/). Recognising the limitations of travel-time tomography for monitoring a disposal cell, which will have dimensions of only a few metres, full waveform inversion techniques have being employed to enhance the capacity to monitor remote from the excavation.

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 to perform the inversions.

5.1.2 Key programme challenges

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 to the elastic properties of the medium under investigation. These variations in 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.

5.1.3 Experimental configuration

An experimental test site has been established at Grimsel Test Site (GTS). The layout is sketched in Figure 5-1-1. 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, 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.

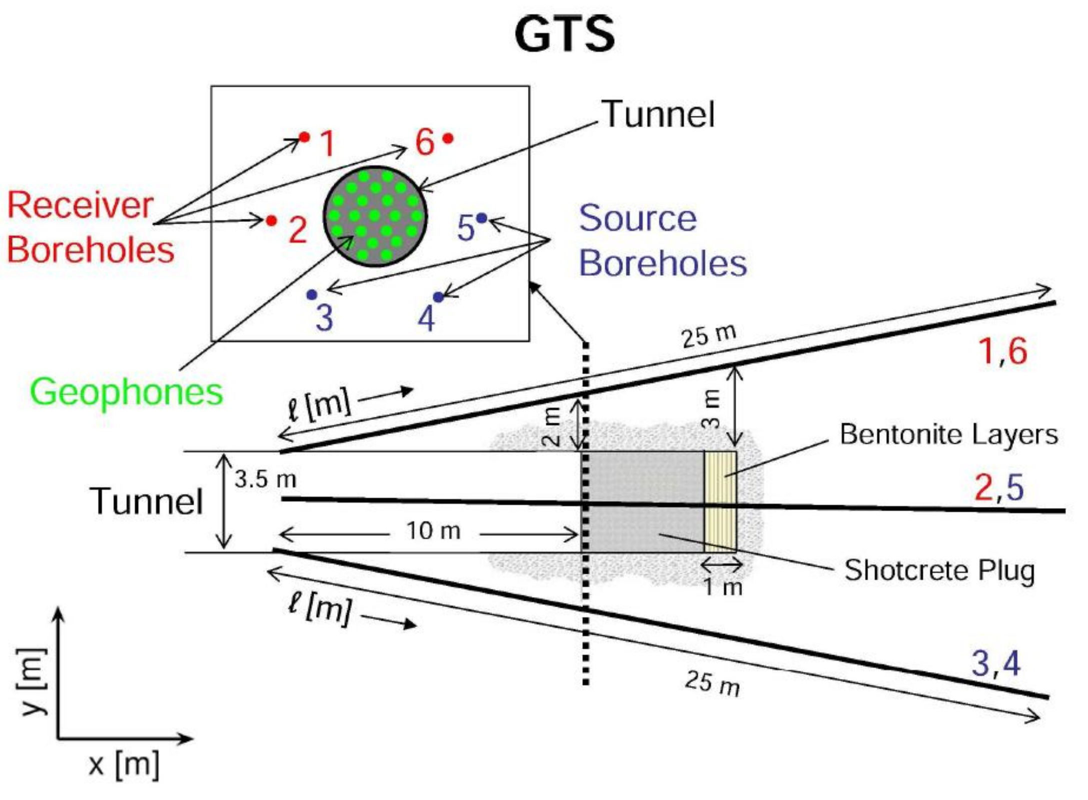

Figure 5-1-2: Layout for seismic tomography at GTS

5.1.4 Results of demonstration activities

Data accuracy requirements

To quantify waveform changes expected to be caused by physical property changes within and around the simulated repositories at the Grimsel, numerical modelling experiments were performed. End-member scenarios were considered for the Grimsel site synthetic experiment: a dry and a fully water-saturated bentonite block.

Figure 5-1-3 shows the results for a selected shot position at each site. Wavefield snapshots at a time t = 3.6 ms for the dry and wet bentonite scenarios at Grimsel are presented in Figure 5-1-3a and b, and simulated seismic sections for a hydrophone in borehole 2 are displayed in Figure 5-1-3d and e. Differences between the dry and the water-saturated scenarios, magnified by a factor 2, are displayed in Figure 5-1-2c and f. The snapshots and seismic sections indicate that the process of water saturation generates significant differences in the waveforms to be acquired.

Success or failure of waveform-based inversion relies on its capability to exploit the waveform differences shown in Figure 5-1-3f. This requires data accuracy and repeatability to be significantly better than these differences. Although the (magnified) differences appear to be large, it will be challenging to identify them in observed data in the presence of noise. Nevertheless, it can be concluded that such an endeavour will be feasible, assuming that the field data are of high quality.

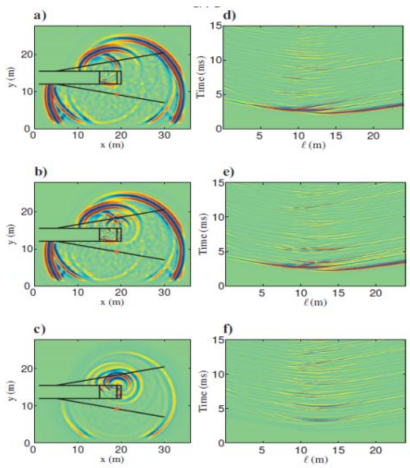

Figure 5-1-3: Simulation results for Grimsel. Snapshots of pressure wavefields at 3.6 ms for (a) dry bentonite and (b) fully water- saturated bentonite (c) Difference between (a) and (b) with amplitudes magnified by a factor of two. Source position is indicated by the red dot in each diagram. Seismic sections as they would be recorded in the receiver borehole are shown in (d) and (e), and the difference seismic section is presented in (f) with amplitudes amplified by a factor of two.

Repeatability of seismic measurements

Repeatability of seismic experiments is governed by several factors, including the:

- source signal,
- coupling of the source to the medium,
- coupling of the receiver to the medium, and

- fidelity of the receiver and acquisition system

To study the effects of these different factors, extensive tests were performed at the Grimsel site. The experiments were conducted when the bentonite block was partially saturated (the actual state of the simulated repositories is not critical for the repeatability tests).

The tests revealed that the sparker source is highly repeatable, and it represents thus a viable option for such monitoring experiments. In contrast, hydrophones offer only good repeatability in the frequency band from about 500 Hz to about 3.5 kHz, and this conclusion is only valid as long as the hydrophones stay in place. When the hydrophones are removed and re-inserted, the coupling changes dramatically, as it is shown in Figure 5-1-4. Consequently, geophones that are firmly grouted in the boreholes should be used. Coupling between the geophones and the host rock can be still quite significant, but the coupling conditions remain constant. Therefore, highly repeatable waveforms can be recorded.

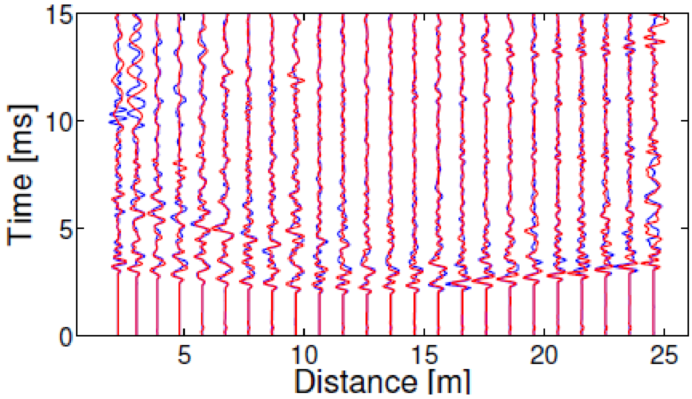

Figure 5-1-4: Shot gathers for repeated experiments before (red traces) and after (blue traces) re-inserting the hydrophone chain at Grimsel test site.

Determining elastic bentonite properties with laboratory measurements

The swelling of bentonite, in which high-level radioactive waste should be embedded, is one of the key targets of seismic near field monitoring. In order to quantify the effects of water saturation, temperature and pressure on the elastic bentonite properties, extensive laboratory measurements were performed. Four different sets of samples with water saturations from approximately 10% to 50% were initially prepared. Due to limitations of the instruments, it was not possible to vary both temperature and pressure. Therefore, a first set of measurements was performed at a constant pressure of about 2 MPa. The resulting P- and S-wave velocities are shown in Figure 5-1-5. The individual curves demonstrate that (i) the seismic velocities primarily depend on the water content and (ii) that the velocities decrease linearly with increasing temperature.

In a second set of measurements the temperature was kept constant at room temperature, and the seismic velocities were measured under different confining pressures. The results are shown in Figure 5-1-6. As expected, both the P- and S-wave velocities increase with increasing pressure. Compared with the varying temperature measurements, shown in Figure 5-1-5, the velocities are more influenced by pressure than the water content. In particular, within the pressure range between 1 and 20 MPa, which is most significant for high-level radioactive waste repositories, the velocities vary considerably as a function of pressure.

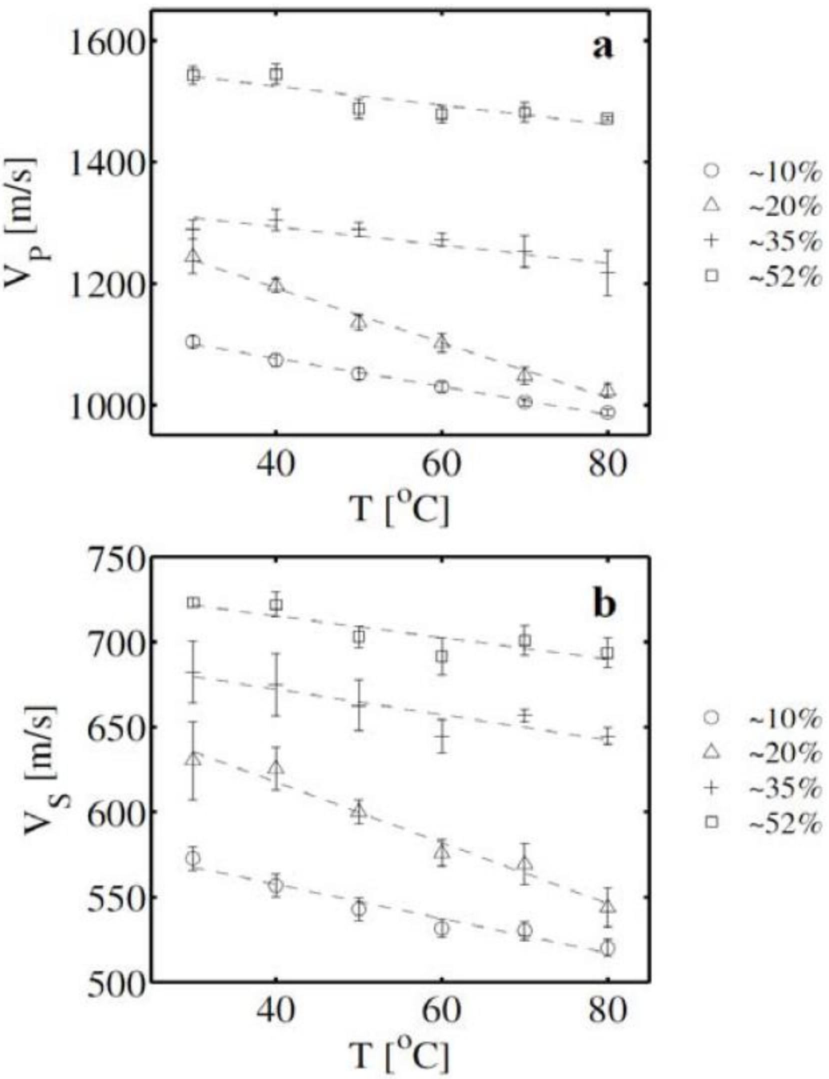

Figure 5-1-5: Seismic P- and S-wave velocities of bentonite as a function of temperature, for different percentages of water content.

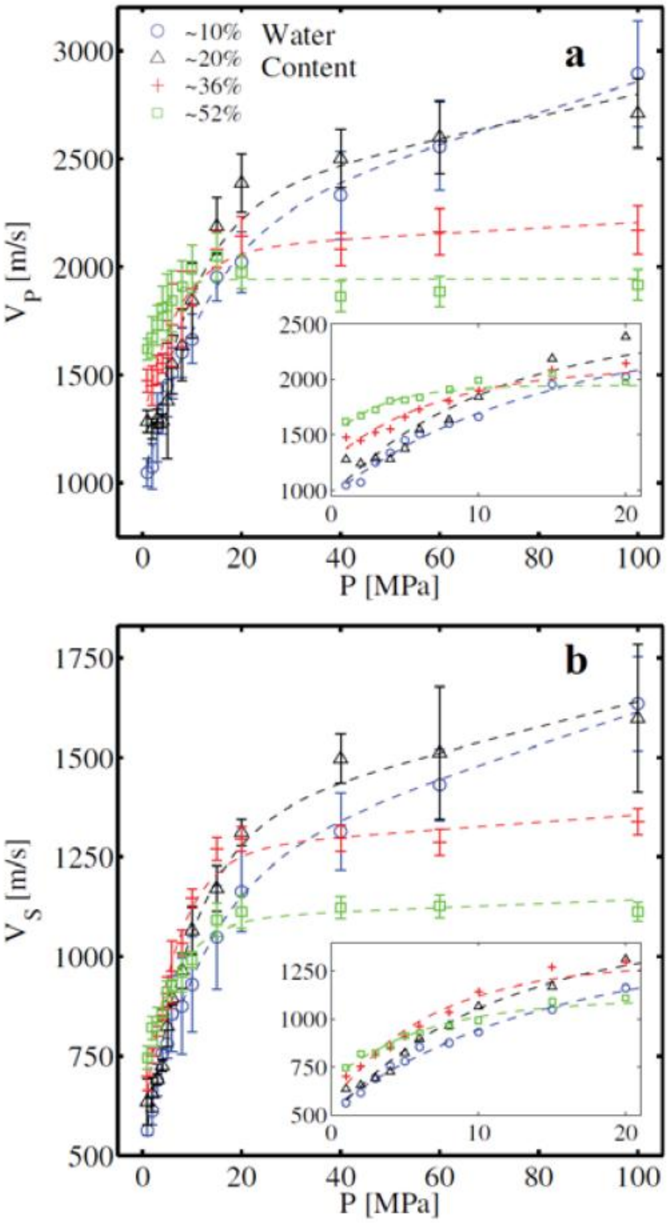

Figure 5-1-6: Seismic P- and S-wave velocities of bentonite as a function of pressure for different percentages of water content. The insets show expanded views of the pressure range 0 to 20 MPa.

Key results from novel developments of seismic full waveform inversions

Besides the demonstration activities discussed above, numerous investigations and developments for seismic full waveform inversions have been performed. The results can be summarized as follows.

1. *Experimental design*
   Criteria have been established for specifying the optimal spatial and temporal sampling strategies for EBS monitoring. In particular, the work has demonstrated that it is essential that the seismic signal used for tomographic imaging includes both low and high frequencies, and that these frequencies can be measured in the receivers. With regard to spatial sampling, the work concluded that the source and receiver spacing along the boreholes is not so critical for conducting elastic waveform inversions, but, instead, it is

essential to have multi-component recording capabilities and, if possible, directed sources.

2. *Validity of the acoustic approximation*
   Extensive numerical experiments revealed that the acoustic approximation used to translate seismic waves into a velocity structure is not adequate for monitoring radioactive waste repositories. Elastic inversion schemes should be used instead. However, acoustic waveform inversions are the current state-of-the-art, and elastic inversions are the topic of current research and require further development.

3. *Non-linearity issues*
   The mathematical formulation used to transfer the seismic waveform information into a velocity model is highly non-linear, and it is therefore challenging to develop algorithms to undertake the necessary calculations. The work in the MoDeRn Project has identified where currently-available algorithms are expected to be successful and when they are likely to fail. Furthermore, the potential for undertaking successful translation of the seismic waveforms to a velocity model depends on the availability of *a priori* information, i.e. a detailed velocity model for the area of interest acquired before the monitoring of changes is undertaken. Acquisition of a detailed velocity model is considered feasible for dedicated repository tomographic monitoring. It has been shown that non-linear effects increase when the contrast between the velocity of the EBS and the host rock is more pronounced. This means that non-linear issues are more challenging in a granitic host rock, compared with a clay environment, as the seismic velocity of granite is higher than clay.

4. *Anisotropic inversions*
   Suitable host rocks may exhibit a high degree of anisotropy, for example the layering within sedimentary rocks can impose a strong anisotropy parallel to bedding. The algorithms used to convert seismic signals to a tomographic image need to account for the anisotropy, and such algorithms were not available prior to the MoDeRn Project. Anisotropic and elastic waveform algorithms have been successfully developed, and initial synthetic inversions have been undertaken to demonstrate the suitability of using these new algorithms for monitoring sedimentary rocks using seismic tomography.

5. *Coupling problems*
   Sensor coupling to the host medium is a critical issue. An algorithm has been developed and successfully tested and can be used to reliably determine the coupling factors. In addition, practical work undertaken within Mont Terri has demonstrated that only firmly grouted geophones that are cemented into boreholes allow seismic signals to be captured with sufficient accuracy to allow full waveform inversions to be undertaken. Although the coupling problem persists when geophones are grouted into boreholes, the coupling factors are constant, and, therefore, the algorithm developed within the MoDeRn Project can be used to overcome this problem.

5.1.5 Lessons learned

On the basis of the results obtained, seismic waveform tomography is judged to be a promising option for non-intrusive monitoring of radioactive waste repositories. Once the outstanding problems are resolved, it is recommended that further monitoring experiments are performed, preferably at a realistic scale. Since different host rocks will impose different challenges on such seismic experiments, it is further recommended that experiments are performed simultaneously in different potential host rock environments (granitic rocks, clays, salt). Although seismic waveform tomography is still viewed as the most promising techniques, there are potential benefits from geoelectric or electromagnetic methods, which may provide additional diagnostic information in the form of host rock electric parameters.

5.1.6 Issues for further R&D

The work on seismic tomography in the MoDeRn Project has illustrated the potential feasibility of monitoring the EBS using full waveform elastic inversions of the recorded seismic waveforms. However, acoustic waveforms are the current state-of-the-art, and further development of the elastic method is required.

At present, seismic tomography techniques have progressed sufficiently to be confident that velocity changes within an EBS can be monitored. However, further work is required to relate velocity changes to specific processes, i.e. to allow the measured changes to be related to saturation, gas generation, thermal expansion or other near-field processes. In addition, consideration would need to be given in the safety case for the possible influence of backfilled monitoring boreholes close to the EBS, i.e. whether there could be sufficient confidence in their sealing so that they would not be considered as a radionuclide migration pathway in the safety assessment.

Further consideration of equipment reliability and durability is also required. Although the research within the MoDeRn Project yielded several new insights on how to conduct seismic waveform experiments, there are still open questions that require further research. The most urgent areas, where further knowledge is required are:

- The need to explore, which type of seismic sensors would most be suitable for future monitoring experiments,
- More research to test the durability and reliability of the seismic equipment,
- The investigation, in more detail, of the sensor coupling problem, and
- Further algorithmic development to apply this promising technique to realistic data sets.

5.2 High Frequency Wireless Sensor Networks

This research evaluates the capacity for remote transmission of information from sensors embedded within a monitored disposal cell to an external receiver using high frequency wireless transmission (non-intrusive technique), as a means of avoiding the barrier(s) being disturbed by the use of connecting cables. This work has been lead by ENRESA, the Spanish radioactive waste management agency) with the support of AITEMIN (Association for Research and Industrial Development of Natural Resources, Spain).

A more detailed report on this work has been published within the MoDeRn Project (MoDeRn, 2013e and MoDeRn, 2013n)

5.2.1 Objectives and rationale

The developed wireless transmission technique has been implemented for testing on the same shotcrete plug at the Grimsel Test Site (GTS) as that used for seismic tomography demonstration (See 5.1). This activity is aimed at demonstrating, under realistic conditions, the potential for underground use of high frequency wireless (HFW) nodes to build data transmission networks of conventional sensors, which would be immersed in solid material (buffer, concrete, rock, etc.). It also addresses the management of the corresponding energy needs for operating in an inaccessible location over decades. Initial work under this programme focused on designing appropriate wireless nodes by evaluating, at different frequencies, the limiting distances for remote transmission through solid media and the capacity and rate for transmitting data at those frequencies relative to energy requirements.

The aim is to obtain HFW nodes capable of incorporating up to four conventional sensors, providing the integral power supply and gathering the data remotely from all of them. The data obtained by the HFW nodes will be transmitted through the plug to 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 conventional hard-wired monitoring systems.

The demonstration exercise comprises the installation of five HFW nodes, two of them installed in the bentonite buffer through boreholes drilled in the shotcrete plug and three more units located in boreholes drilling in the shotcrete plug and the rock mass. The parameters to be measured are: pore pressure, total pressure and water content.

The primary purpose of the test was to evaluate the performance of HFW networks in transmitting data from the sensors to the control system and the expected data life when using batteries as energy source under realistic conditions. Additionally, the feasibility of power harvesting to conserve the power source (battery) and to extend the period of monitoring were also evaluated.

5.2.2 Key programme challenges

For wireless sensors to operate effectively while buried within the disposal cells components, (buffer, concrete, rock, etc) requires a number of specific problems to be addressed:

1. They should be capable of withstanding the operation conditions: buried, high mechanical and hydraulic pressures, relative high temperatures, radiation, etc.
2. They should be of reduced size to minimise the effects on the barrier.

3. They should have a long enough life time to provide the required information during the first phase of the engineered barrier maturation.
4. They should have enough range to transmit the information to the receiver, located at a distance of at least 5-10m.

5.2.3 R&D to address challenges

Wireless transmission methods are totally non-intrusive with the environment, although they have some limitations, such as the attenuation of the signal caused by physical properties of the media e.g. humidity or materials density, and the relative high power consumption needed to get the signal to pass through certain components, such as a thick wall of concrete.

Frequency selection and laboratory testing

The first step was to determine the most suitable frequency for the target application, given that the industry offers a wide range of wireless products working at thousands of frequencies along both radio and magnetic spectrum. To focus effort onto a reduced number of candidate frequencies, both the knowledge and past experiences of successes were taken from others European research and development projects such as RAINOW (Contract Number: RFCR-CT-2005-00003) where wireless systems for use in harsh environments were also developed. Based on these previous experiences, VHF and UHF band (high frequencies) were selected as the most suitable to be applied to the planned wireless system.

One of the main advantages of high frequency is the higher data rate capability in comparison with lower frequency bands (ULF, SLF, ELF). It means shorter transmission times and lower power consumption. On the other hand, the penetration of lower frequencies through solid materials is much deeper, mainly for those based on magnetic fields (<150KHz).

Within the VHF and UHF bands, there are four sub-bands assigned for Industrial Scientific and Medical (ISM) purposes. These bands are free to use (no licenses are required) and the market offers factory-adjusted and calibrated devices aimed at working in those bandwidths to meet the transmission parameters established in the ITU (International Telecommunication Union) regulations. However, these frequencies have a significant problem, which is also accentuated by the particular working environment of this application: the influence of water or humidity on the wireless signal, which can cause very high attenuations and consequently significantly reduce the transmission distance.

To understand the behaviour of candidate frequencies in conditions similar to a disposal scenario, specific tests were performed in AITEMIN labs using a shielded radio propagation tube. This tube (shown in the image below) contains an interchangeable central part where some of the materials including bentonite, salt water and rock (argillite) planned for the demonstration, were tested. The transmission distance for high-frequency signals at four frequencies were tested in the laboratory, and in the field (at the El Cabril low-level radioactive waste disposal facility and the Tournemire URL). The frequencies tested were 2.4 GHz, 868 MHz, 433 MHz and 169 MHz. In laboratory tests, signals at 868 MHz and 433 MHz were capable of passing through 50 cm of bentonite, 25 cm of salty water and 40 cm of argillite rock; transmission distances at 2.4 GHz were lower. Field tests demonstrated that transmission distances at 169 MHz were greater, about 3.5 m in clay-based rocks and greater than 5 m in saturated bentonite, and this frequency was adopted for the demonstration tests in the MoDeRn Project.

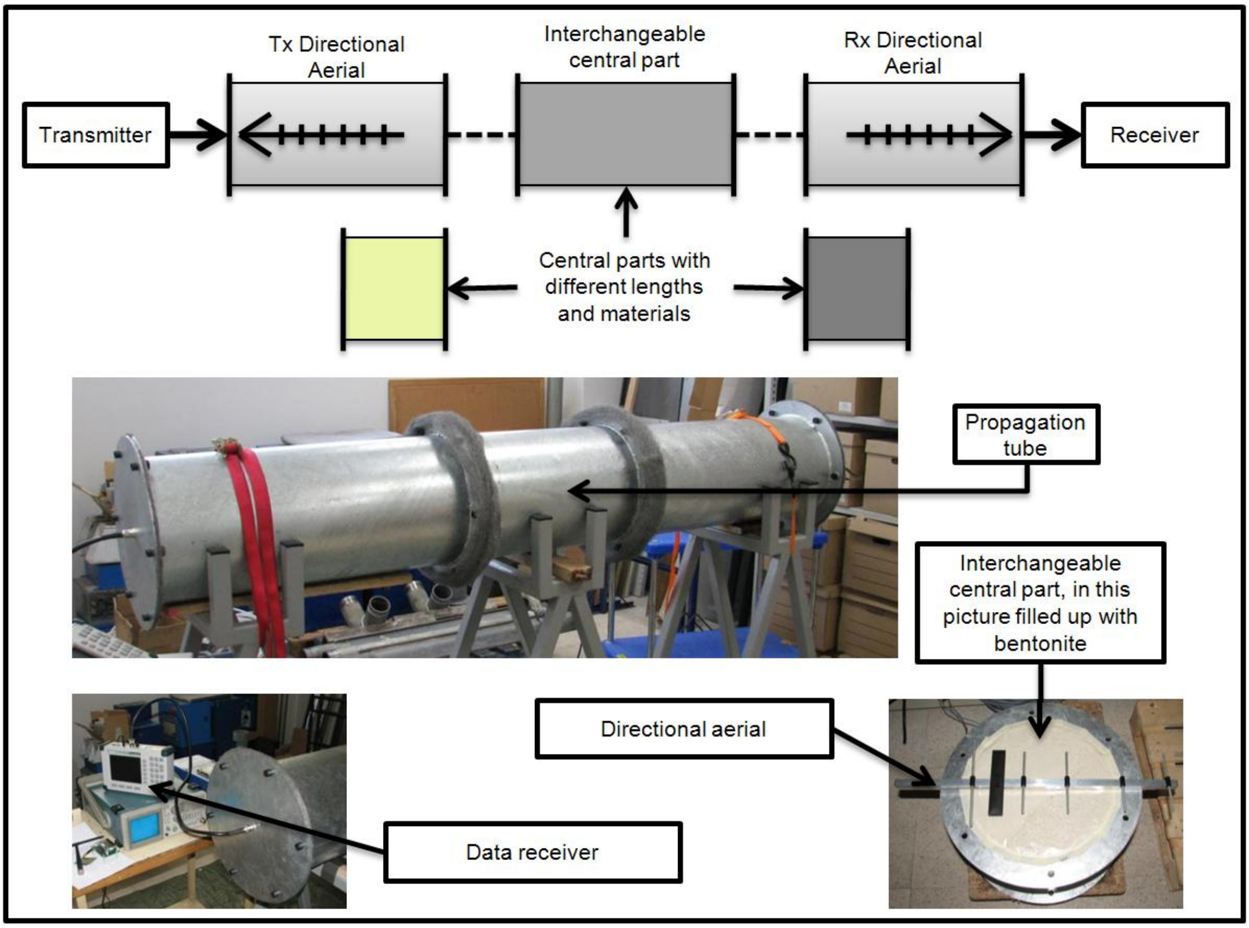

Figure 5-2-1: Shielded propagation tube used during lab tests

Field testing

Testing of penetration capabilities for the VHF band has some limitations when using the propagation tube, because the wavelength of those frequencies are larger than tube diameter, so additional tests were performed in two mock-ups located in El Cabril (Spain) and Tournemire (France).

Based on the results obtained, the most suitable frequency to be used as carrier in the radio transmission stages was selected.

Figure 5-2-2: Testing at El Cabril and Tournemire

System architecture and design

The development of the different parts of the system was performed using radio transceivers (two way radio systems) tuned at the selected frequency (see main characteristics at the table below). The use of bi-directional and also multi-channel radio interfaces allowed: the system both to change the behaviour dynamically by means of sending remote commands to the wireless nodes; and the co-existence of more than one independent monitoring system in the same scenario without causing interferences.

Table 5-2-1: Main wireless monitoring system features

Main System Features	
Period between readings/transmissions	5 min to 12 hours (can be changed remotely)
Radio signal penetration (approx.)	Clayey rock: ≈3.5m and Bentonite: >5m.
Expected battery life	Depending on transmission period (up to more than 20 years).
Number of analog sensors per node	4 (voltage and current)
Number of digital sensors per node	3
Power supply for sensors	Provided by node battery. Max. $12V_{DC}$
Master unit connectivity	Ethernet, MODBUS TCP.
Master unit power supply	$12/24V_{DC}$, 1A.
Wireless units per master controller	16 max.

The architecture of the wireless system is made up of a master controller, (installed in accessible and safe zone), a wireless receiver and various wireless nodes placed into the sealed area (see Figure 5-2-3).The master controller (or nodes coordinator) manages transmission synchronisation issues, sensor data gathering and real time display, as well as the data conversion and exchange with third parties (e.g. this allows the system to be easily integrated with any commercial SCADA for long term data logging).

Figure 5-2-3: Wireless master controller and HFW node prototype

Power source

Once the wireless nodes are installed they are no longer accessible. This condition requires the devices being powered to use a reliable and long life energy source. There are basically two ways to get energy to power the wireless nodes: i) by means of batteries (stored energy); or ii) harvesting energy from the environment, when possible.

Analyzing the power requirements of the wireless nodes, it was observed that the average power consumption of each node, including “keep alive” base current, data transmission, remote commands reception and sensor powering and measuring it is only some tens of microamps. The actual average current depends on how often the measure-reading-transmission cycle is performed. Considering an average current demand of 250µA (estimated for 1 transmission per hour) with a standard voltage of 3.3 Volts, the average power needed by the wireless node is 825µW.

Energy harvesting

After some research about the available methods to harvest energy from within the sealed-off area, the most “feasible” one was the thermal gradient. This draws energy from the difference in temperature between two points based on the Seebeck effect, for example, between the canister surface and the rock.

Laboratory tests were carried out taking a temperature difference of 15 degrees as a reference starting point in a real scenario. From the results obtained, the real power provided (useful power available for the wireless node) was 1100µW approximately (333µA@3.3VDC), which appears sufficient energy to supply the node (1100µW > 825µW), however, analyzing the power requirements of the node over time, it was observed that almost the 80% of the energy is required in less than 1 second. This means that a storage method is required to be able to collect enough energy during inactive periods and to use it during sensor reading and data transmission.

The use of super capacitors (new generation of high capacitance capacitors) was evaluated as energy storage system but it was found that the leakage current of the capacitor (wasted energy) is in the same order as that needed by the wireless node to function. In addition super capacitors have a short life time.

For the reasons cited above the conclusion is that the use of energy harvesting, such as thermal gradient, can provide enough energy to transmit information, however the energy storage elements, indispensable to support demand peaks, are not suitable because of both of energy leakage and short life time of the super capacitors.

Battery

The alternative is the use of batteries to power the wireless nodes. The use of lithium-thionyl chloride (Li-SOCl2) batteries over many years has proven their reliability and good performance. Having a self-discharge coefficient between 1 to 3% per year, some devices are still working with this type of batteries after 25 years. Nowadays their improved chemical make-up allows for even longer life, more energy density and a wider operating temperature range. On the other hand, the relative high intrinsic serial resistor limits their current peak capabilities.

The designed wireless nodes include a Li-SOCl2 battery combined with some high performance capacitors (only some hundreds of µF, not catalogued as ultra capacitors) that support high current demands having a very low leakage current (only some nA). The result is a small self-contained device (with no extra requirements to harvest energy) with an expected lifetime up to 20 or 25 years.

5.2.4 Experimental configuration

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. The laboratory tunnel has a diameter of 3.5 m and was bored in six months using a full-face tunnelling machine (TBM). The wireless transmission technique demonstrator was implemented at the so called low-pH plug test, (built during ESDRED IP project – (http://www.esdred.info/) which is located at the end of the VE tunnel, close to the GMT experiment (see figure below).

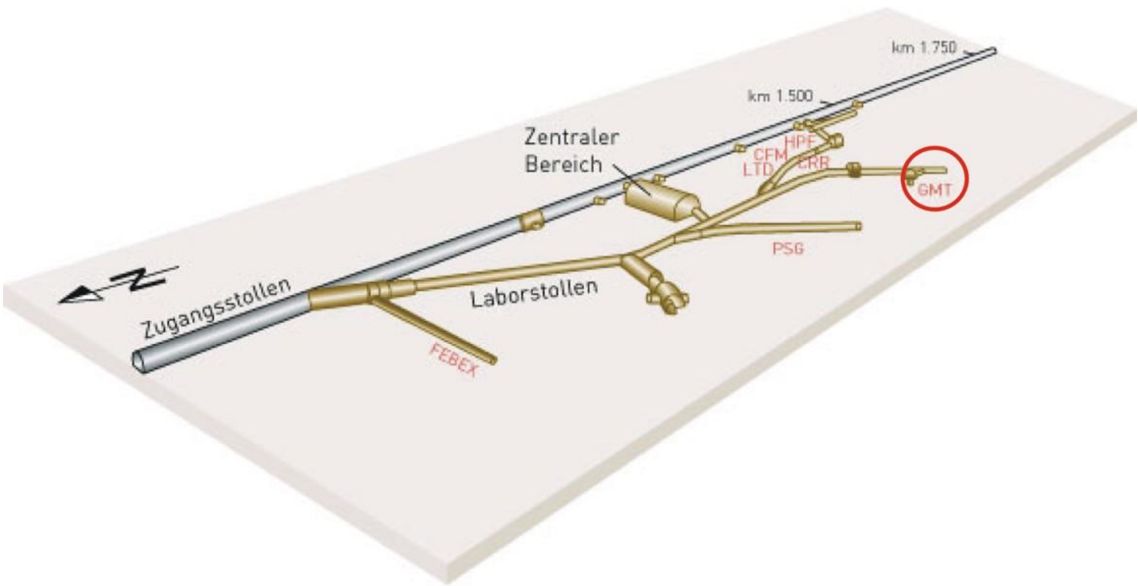

Figure 5-2-4: Location of the full-scale test at VE tunnel.

The basic layout of low-pH plug test consists of a 4 m long parallel shotcrete plug constructed at the back end of the VE tunnel, sealing a 1 m thick buffer of highly compacted bentonite (see Figure 5-2-5).The bentonite was provided with an artificial hydration system to accelerate the saturation process. A number of conventional sensors (wired) were installed at different locations in the rock, in the bentonite and in the shotcrete mass to monitor the plug performance during the test. These sensors were connected to a data acquisition system (DAS) for the monitoring and management of the test.

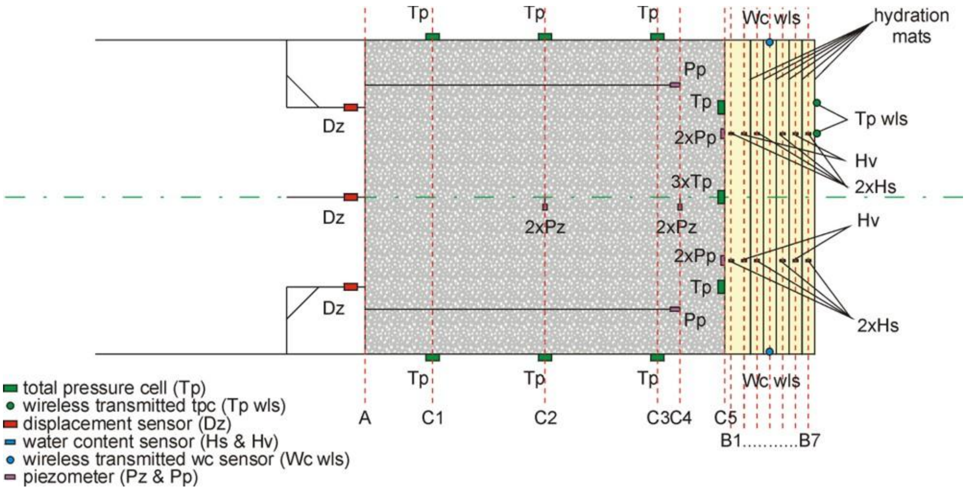

Figure 5-2-5: General layout of the full-scale test showing the layout of instrumentation (wired transmitted sensors only)

A total of five HFW nodes, a receiver and a controller (Figure 5-2-6) were produced to build the wireless transmission technique demonstrator. Figure 5-2-7 shows a sketch of a HFW node, which can measure pore pressure, total pressure, relative humidity and temperature. Two of them were configured to be installed in the bentonite and therefore to measure pore pressure, total pressure and relative humidity, whereas the other three nodes that had to be placed on the rock and the shotcrete plug, were configured for measuring pore pressure only.

Figure 5-2-6: Left, wireless nodes and receiver unit; right, controller unit.

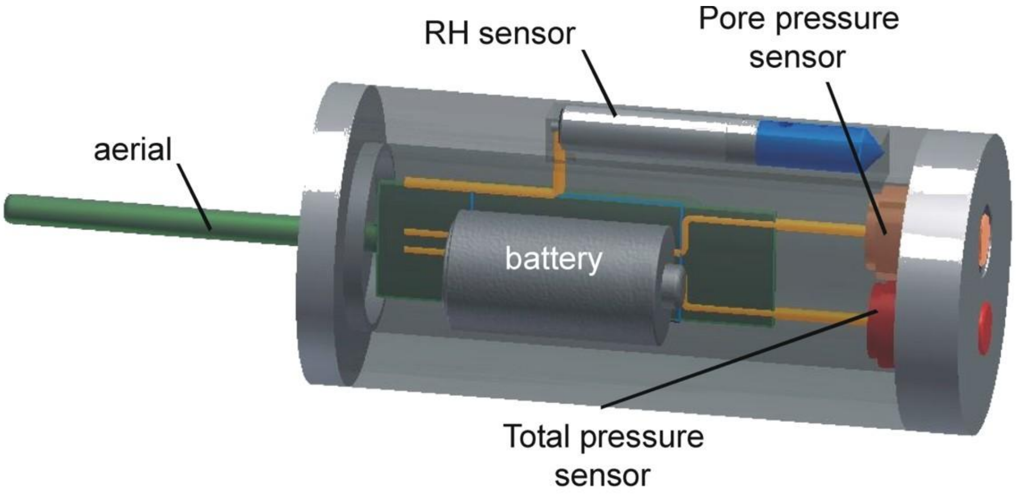

Figure 5-2-7: Sketch of a HFW node.

Five boreholes with an inner diameter of approximately 86 mm were drilled by the end of October 2011, four at the plug and one in the rock, to house the five HFW nodes. Then, during the first week of November 2011, the HWF nodes were manually installed in the boreholes and several tests were performed to assess the viability of the system.

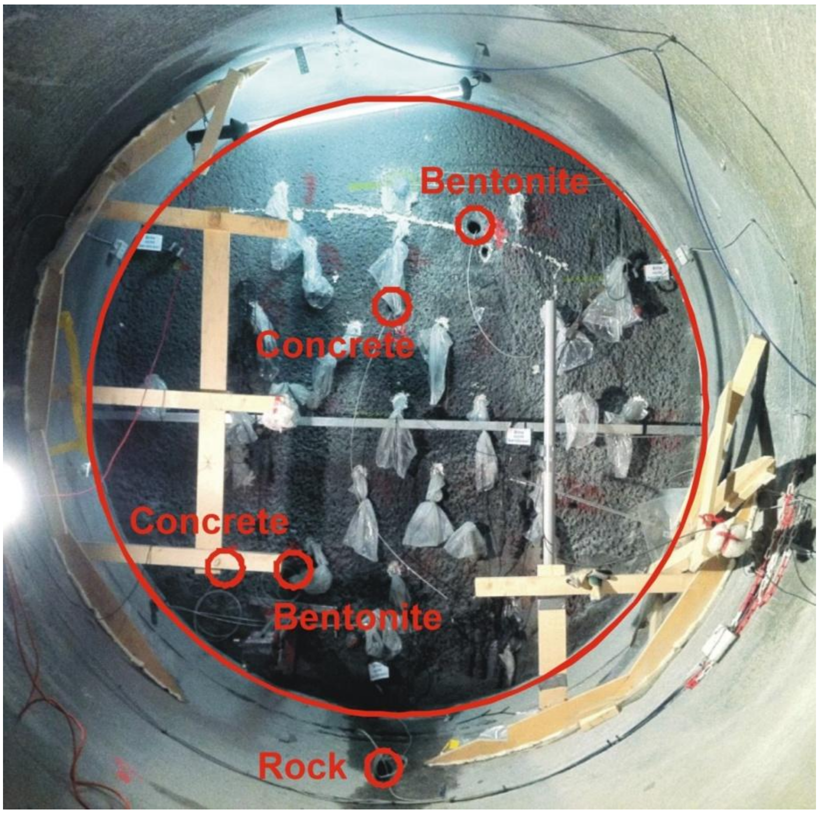

Figure 5-2-8: Position of the five different boreholes

Figure 5-2-9: Detail of node before installation

The next step was to build the sensor node network, including a receiver and a controller connected to the main DAS. The proper behaviour of intercommunication between devices and data gathering was assessed. After a period of time to verify that the system was properly running, the boreholes were filled up with a concrete-based filling grout, in March 2012.

5.2.5 Results of demonstration activities

The demonstration exercise comprised the installation of five HFW nodes. Two of them were installed in the bentonite buffer through boreholes drilled in the shotcrete plug. The parameters being measured in these units are: pore pressure, total pressure and water content (relative humidity). The remaining three sensing units were installed in the concrete plug and in the rock mass, two of them to measure pore pressure in the plug and the last one measures pore pressure in the rock around the bentonite buffer (below the plug). A scheme of the overall layout including the precedent instrumentation is shown on figure 5-2-10.

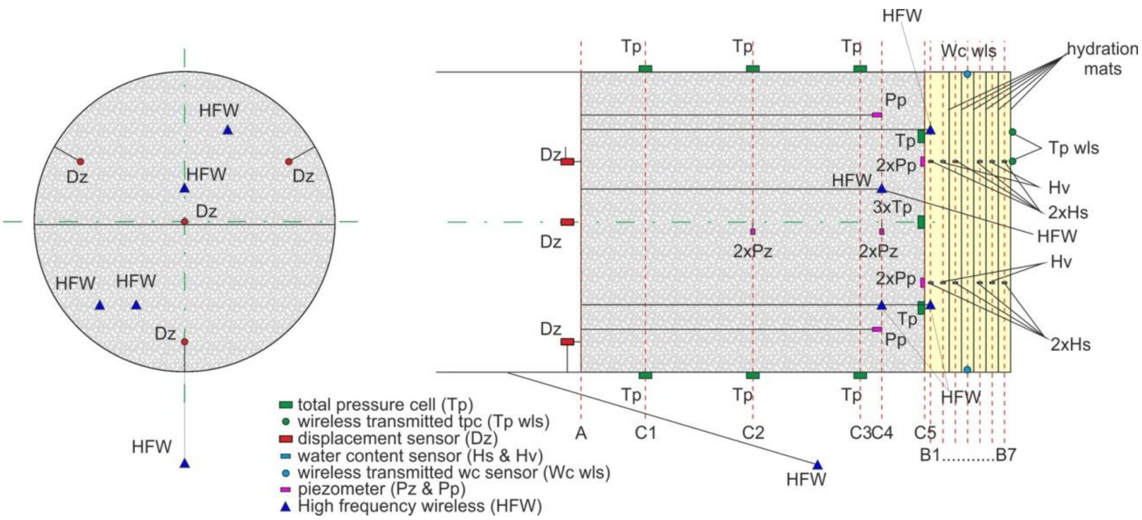

Figure 5-2-10: Layout of installed instrumentation (including HFW)

The up-to-date performance of the HFW system can be summarized in the following points;

- All nodes installed are transmitting successfully;
- Data is being collected and stored correctly;
- Bentonite is already pressurising the HFW nodes;
- Sealing of boreholes has not significantly affected signals' transmission; and
- Further monitoring time could be appropriate to assess the proper functioning over a longer period of time.

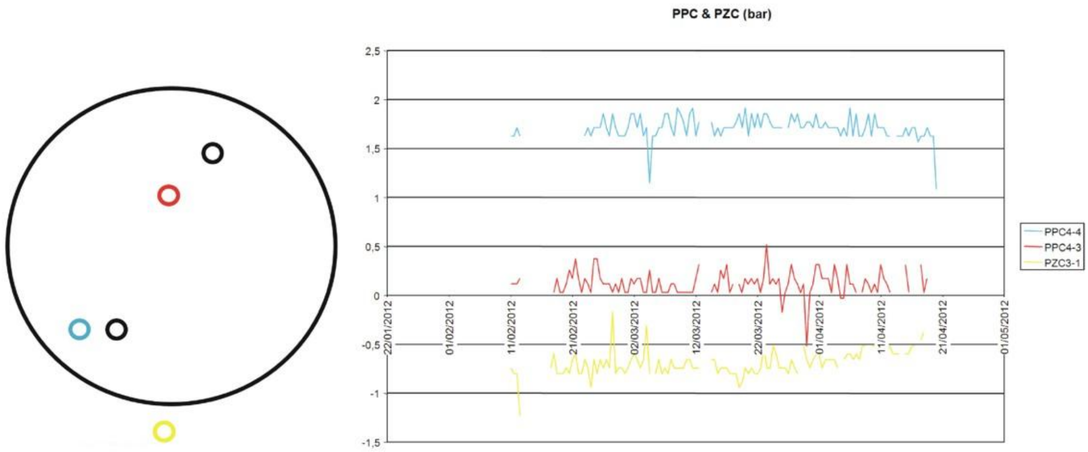

Figure 5-2-11: Example of data gathered from HFW nodes

5.2.6 Lessons learned

The designed wireless data transmission system based on high frequency nodes (HFW) has fulfilled the requirements to provide a short-range local monitoring network, coupled to conventional sensors, in a sealed-off area avoiding the use of cables (non-intrusive method). The nodes are small in size and made with highly resistant materials and are capable of withstanding the harsh condition inside bentonite, rock, concrete or other similar materials used in the construction of disposal facilities. Although the lifetime is short in comparison with the evolution of the monitoring areas, this first version is in principle capable of providing data for the first 20 years or more. The transmission is made point to point at a distance that ranges between 3 to 10m depending on the material sealing of the units and its degree of water content.

5.2.7 Issues for further R&D

Further research and future works will be needed at least to extend the operating life time and improve signal penetration, so in particular the issues for further R&D are as follows:

- Explore new methods for harvesting and, importantly, storing energy, in order to extend the HFW nodes lifetime.
- Incorporate additional types of sensors to the nodes, for instance, vibrating wire, psychrometers, fibre optics, Wheatstone bridge, etc. to extend the range of parameters that can be monitored.
- Further reduction of the node's components size (miniaturisation) to reduce the media alteration.
- Evaluation of performance under ionising environment (radiation) and shielding if required.
- Improvement in the reliability and redundancy of some components to extend the lifetime.
- Improvement of the transmission range and reliability by using:
    - directive embedded fractal aerials;
    - antenna diversity;
    - better modulation;
    - by-phase codes.
- Implementation of signal hopping to achieve longer transmission distances.
- Coupling with long range wireless data transmission systems (low-frequencies) to communicate from the underground repository, data gathered, using the short range wireless network, to the surface, in one step.

There have been several theoretical solutions proposed for transmission of data from repositories to the surface. These include signal hopping (relaying data through media by using a series of appropriately placed wireless nodes) and coupling of high-frequency systems with long-range, low-frequency data transmission systems. Whilst, in theory, these approaches appear feasible, practical demonstration of these approaches has not yet been undertaken. Practical demonstration is required to identify problems limiting the practical use of such systems in operating repositories and to identify solutions to these challenges. Demonstration would also support optimisation of the approaches envisaged.

5.3 Fibre optic sensing, micro-seismic techniques, and monitoring of Supercontainer

Within the MoDeRn project, EURIDICE and ONDRAF/NIRAS are deploying two rather innovative monitoring technologies in the framework of the PRACLAY Heater Test, a demonstration at near-real scale of the effects of disposal gallery with heat-dissipating HLW on a clay host formation in the HADES URL at Mol, Belgium. This work programme also includes monitoring of the Belgian supercontainer which is part of the Belgian reference concept proposed by ONDRAF/NIRAS for packaging of HLW and spent fuel (SF).

The first technology is based on fibre optic sensing. Two main principles are considered: distributed monitoring based on scattering, and interferometric sensing to detect extensions along rather long measurement bases (5 and 10 m).

Optical fibres can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fibre so that the quantity to be measured modulates the intensity, phase, polarization and wavelength or transit time of light in the fibre. Data can also be collected from unmodified optical fibres from the backscattering of light out from the fibre. Three scattering modes can be used to monitor different parameters. Raman scattering (using multimode fibres) can be used to monitor temperature. Brillouin and Rayleigh scattering (using single mode fibres) can be used to measure strain and temperature over large distances (Rogers, 1999; Lanticq et al., 2010).

The interpretation of data acquired using optical fibres is based on calibration against known responses to parameter changes. This requires determination of optical fibre characteristics (e.g. shifts in the intensity and frequency of the light as a function of change in temperature and strain), and assessment of installation-related issues. Each installation has its own characteristics, such as the way the fibre is fixed, the number and quality of splices (connections), and the type of connectors. Partly, the calibration can therefore be performed by the manufacturer before the installation, but to achieve the full potential of accuracy, an in-situ calibration is required. This is usually performed by adding classical temperature sensors, such as Pt100 sensors or thermocouples, next to the fibre at specific locations.

The second monitoring technology uses the micro-seismic properties of the clay host formation on metre-scale to visualise the quality of the clay, and to monitor the changes due to the different impacts (excavation, ventilation, saturation, heating).

Micro-seismic events are localised seismic phenomena that can originate spontaneously during stress release (or build up) in the rock mass, for example after an excavation, and are the result of the mechanical response of the rock. They can also originate during the emplacement of the waste or induced manually by generating small seismic oscillations using a hammer or another type of signal generating source against the rock mass. Seismicity results also from the sudden release of accumulated strain energy during the initiation and propagation of discontinuities in rock (e.g. joints, fractures and faults). The frequency of the emitted seismic signals typically ranges from less than 1 Hz (infrasonic) to 1 MHz (ultrasonic), with the characteristic frequency of the events being dependent upon the scale of the event occurring at the rupture surface and the seismic properties of the rock mass.

Micro-seismic monitoring may allow monitoring of the near-field response to waste and EBS emplacement. This monitoring could be undertaken prior to the closure of the access ways and service areas in the repository.

A more detailed report on this work has been published within the MoDeRn Project (MoDeRn, 2013f and MoDeRn, 2013n)

5.3.1 Objectives and rationale

Fibre optic sensing

Optical fibres may be selected for monitoring because of the small size of the fibres and because of their inherent multiplexing capabilities - many sensors can be combined along the length of a fibre by using different wavelengths of light for each sensor, or by sensing the time delay as light passes along the fibre through each sensor. These qualities make optical fibres suitable for repository monitoring; they provide an efficient means of monitoring a range of parameters. The principal application for fibre optic sensors in repository monitoring is the measurement of parameters such as strain, pressure and/or temperature within the near-field. Fibre optic sensors provide distributed monitoring and, as such, would be suitable for monitoring the 3D parameter-field rather than the single location measured by traditional measurement devices.

However, monitoring data acquired using optical fibres is typically transmitted using wires, but data acquired through the use of optical fibres following emplacement of waste and backfilling of emplacement areas should be transmitted by wireless systems to ensure pathways are not created through key parts of the EBS (e.g. plugs and seals), and specific strategies would require development to ensure that the deployment of optical fibres did not affect the safety functions of the barriers being monitored.

In addition, power is required to generate the light source used with the sensors. Laser-based fibre optic sensors have high power consumption and are therefore not generally considered useful for monitoring the EBS following waste emplacement. Light-emitting diodes (LEDs) have lower power consumption and are generally regarded as more appropriate for repository monitoring, even though commercially available fibre optics currently all use lasers.

Alternatively, optical fibres could be emplaced in repositories in which pre-closure management was used to keep the option for retrievability open, and monitoring of the emplaced packages was used to optimise the design applied later in the programme (see discussion of the illustrative programme for monitoring of HLW disposal cells in the French geological disposal concept in Chapter 5.5).

The PRACLAY Gallery at the HADES URL is undergoing a 10-year long experiment utilising artificial heating 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.

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 applications. The use of fibre-optic sensing, in particular, distributed sensing, has the potential to significantly reduce the number of cables required to pass through seals or barriers while being able to retain a large number of monitoring points within the disposal cell. Fibre optic sensing has been progressed for two applications: temperature monitoring along a fibre using distributed monitoring, and long-base extensometry through interferometric sensors. The monitoring approach of distributed sensing is based on "the fibre is the sensor". This work includes the need for extensive analysis to calibrate the sensors and to compensate for strain-induced errors – as both measurement principles are also affected by strain in the fibre. The impact of the heating on previously installed optical fibres is also being monitored.

Three sensors have been installed in series in each of three 20m long boreholes 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 consist of two fibres inside 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 aim of this work is to improve our understanding of the use of optical fibre for this technique and what adaptations might be required for this type of sensor.

The main phase of the Heater Test – the heating itself – has not yet started due to the performance of the gallery seal, which has not yet obtained the required level due to the slow hydration and swelling of the bentonite.

The Supercontainer Test, simulating the manufacturing of a waste package according to the Belgian supercontainer test, also contains the demonstration of several innovative monitoring techniques, including fibre optics (Fibre Bragg Gratings), corrosion monitoring using different principles, Time Domain Reflectometry (TDR) and Digital Image Correlation (DIC). Within MoDeRn, monitoring inside concrete (or more general cement-based materials) is discussed in more detail in other documents (MoDeRn, 2013f and 2013n) but the monitoring techniques will be discussed briefly in this document.

Micro-seismic monitoring

Micro-seismic piezoelectric transmitters installed in the Boom Clay at HADES produce predominantly high frequency signals, above 5 kHz, which favour the generation of P waves. However, above 5 kHz shear (S) waves are not detected by the installation. Recent studies at HADES indicate that it is possible to detect S waves with the current setup when applying a low (5 kHz) pass filter. The results also show that S waves have frequencies mainly below 1 kHz, while P waves are detectable at all of the eight transmitted frequencies but show optimum resolution in the range of 7 to 23 kHz.

Although the system offers great potential for monitoring the evolution of a geological disposal site, further improvements in signal generation and treatment are necessary. This includes the design and testing of a new S-wave source as part of the MoDeRn programme at HADES.

5.3.2 Experimental configuration

The PRACLAY Gallery is part of the HADES URL as shown in Figure 5-3-1 below.

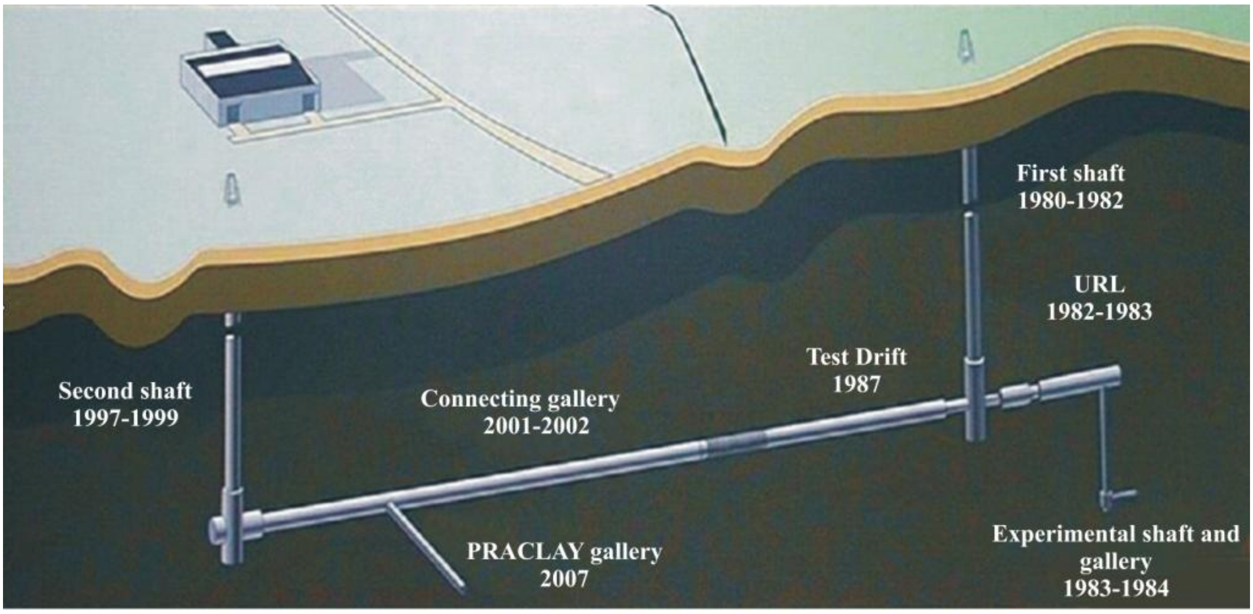

Figure 5-3-1: Schematic diagram of the layout and historical development of the PRACLAY Gallery in HADES URL.

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 $NaHCO_3$ (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 over c. 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.

Fibre optic sensing set-ups

Two main types of optical fibres have been installed:

- Single mode fibres inside a protective tube for distributed monitoring of temperature. Both Brillouin and Rayleigh (spectral shift) scattering are envisaged; fibres with lengths between 60 and 110 m have been installed along monitoring boreholes, as well as inside the gallery itself;
- Interferometric sensors to monitor displacements; for this set-up, we used the commercially available SOFO®sensors from SmarTec SA (member of the RocTest

Group), which have been installed in dedicated extensometer boreholes and in the gallery itself.

Figure 5-3-2 Installation of fibre optic sensor (single mode for distributed monitoring) inside the PRACLAY Gallery

Through these set-up's, it is possible to assess the reliability of fibre optic monitoring technology in repository conditions. The ability to install these sensors, and their performance under high mechanical strains (converging clay) and high hydraulic pressures (up to 3 MPa), can also be assessed.

Micro-seismic monitoring set-up

The installation of the micro-seismic monitoring system consisted of two phases: the first in 2006 prior to the construction of the PRACLAY gallery to monitor the far field; and the second after construction in early 2008 to monitor the near field around the gallery. The ongoing seismic measurements continue to provide information on the evolution of the EDZ around the PRACLAY gallery and in the Boom Clay. In the future, they will also assist in monitoring the thermally disturbed zone (TDZ) around the heater test.

The micro-seismic piezoelectric sensors consist of 23 transmitters (T) and 19 receivers (R). They are installed in three boreholes to depths varying between 0.5 m and 14 m (Figure 5-3-3) as well as at the interface between the gallery lining and the clay host formation.

The shape of the contact surface of the sensors fits the contact shape of the clay to provide a good acoustic contact. Finally, the sensors are made water tight and are sensitive to generate or receive P and S waves in a frequency range between 50 Hz and 100 kHz.

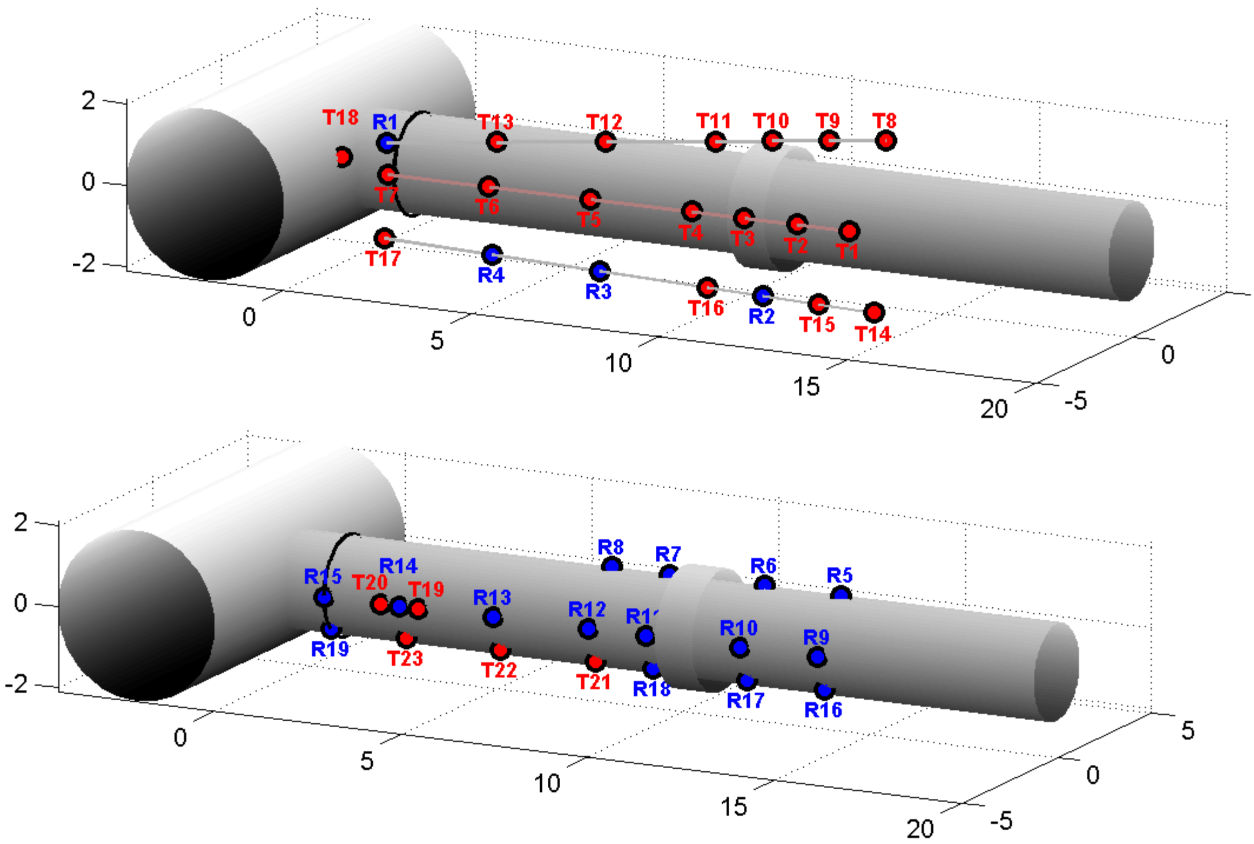

Figure 5-3-3 (above) Transmitters (T) and receivers (R) installed around the (future) PRACLAY Gallery; (below) additional sensors after construction of PRACLAY Gallery

5.3.3 Results of demonstration activities

Distributed sensing monitoring performance

A characteristic feature of the scattering techniques mentioned is their sensitivity to both temperature and strain variation along the fibre, where it is not possible to distinguish which of these has affected the sensor. Through the installation it was established that even the installation of a fibre in a so-called "loose" tube does not exclude the fibre from strain variations along the fibre. These strain variations also change with temperature, so the approach of taking a zero measurement, to which subsequent measurements can be compared, is not sufficient.

The current approach is therefore to use the two scattering techniques that can be used in single-mode fibres: Brillouin and Rayleigh. This way, two independent signals should allow the separation of the temperature and strain component. However, this requires some more development and additional monitoring.

Interferometric sensor monitoring performance

Around the PRACLAY Gallery, three boreholes have been equipped with SOFO® sensors. These boreholes enable the (thermal) extension of the host formation around the gallery to be monitored. Each borehole contains two or three sensors (5 or 10 m long) in series.

Inside the 30 m long gallery, another three sensors (each 10 m) have been installed.

During the testing of the SOFO gauges, two of the nine sensors failed. One of the sensors failed during installation, and another during the subsequent works in the gallery. Both failures are however located in the connecting fibre, and not in the measurement part of the gauge. No installation procedures were available from the manufacturer for installation of the SOFO gauges in this type of setting, and, therefore, an in-house installation procedure had to be developed. This indicates that generic installation procedures need to be prepared for this novel type of sensor for repository monitoring.

The measurements that have been obtained, so far, show that these sensors are able to quantify displacements with a resolution of 1 µm. Based on other quality factors, such as repeatability, the accuracy can be estimated to be less than 10 µm for a measurement base of 10 m. This permits monitoring of very slow movements – typical for long-term repository processes. Also, calibration of inaccessible sensors is not an issue here.

The field performance at higher temperatures (up to 100 °C from the current 15 °C) and higher porewater pressures (up to 2.5 MPa from the current 0.6 MPa) has not been tested yet. The weak points (the protective tube and the anchor points in particular) were made more rugged, but heating of the gallery will be the ultimate test of their resilience.

The use of fibre optics to monitor temperature and strain in the three orthogonal directions in the half-scale test have demonstrated its potential as an in-situ monitoring technology that generates very little disturbance and limited intrusion to the surrounding concrete structure being monitored. However, the measurement instruments needed to interrogate the fibres require direct access to the fibres. This means that the fibres will need to penetrate the structure, a condition that could limit its applicability as monitoring technology in a repository.

Seismic monitoring techniques

Around (a part of) the PRACLAY Gallery, a network of micro-seismic piezo-electric sensors (sources and receivers), has been installed. By monitoring the seismic properties of the host rock, the network enables the assessment of the host rock quality, and its evolution due to different impacts (gallery excavation and lining construction, ventilation, resaturation, heating).

Within the MoDeRn project, we upgraded the set-up by improving the signal conditioning and analysis. The original set-up was based on the analysis of the pressure wave (P-wave) velocity and the damping of the signal. By including the shear waves (S-waves), more information on the rock quality becomes available. Specific analysis of the S-waves is made possible by including lower frequencies (previously these were cut off to reduce the signal noise): in contrast to P-waves, where the best resolution is obtained with frequencies between 7 and 23 kHz, the S-waves mainly contain frequencies below 1 kHz.

The micro-seismic monitoring programme will continue throughout the PRACLAY heater test programme and will provide valuable learning on the use of the newly designed seismic hammer. Continued experience in the recently developed seismic hammer will enhance the ability to generate strong S wave signals to improve shear wave monitoring and continue to provide information on changes to the EDZ as the heating experiment progresses.

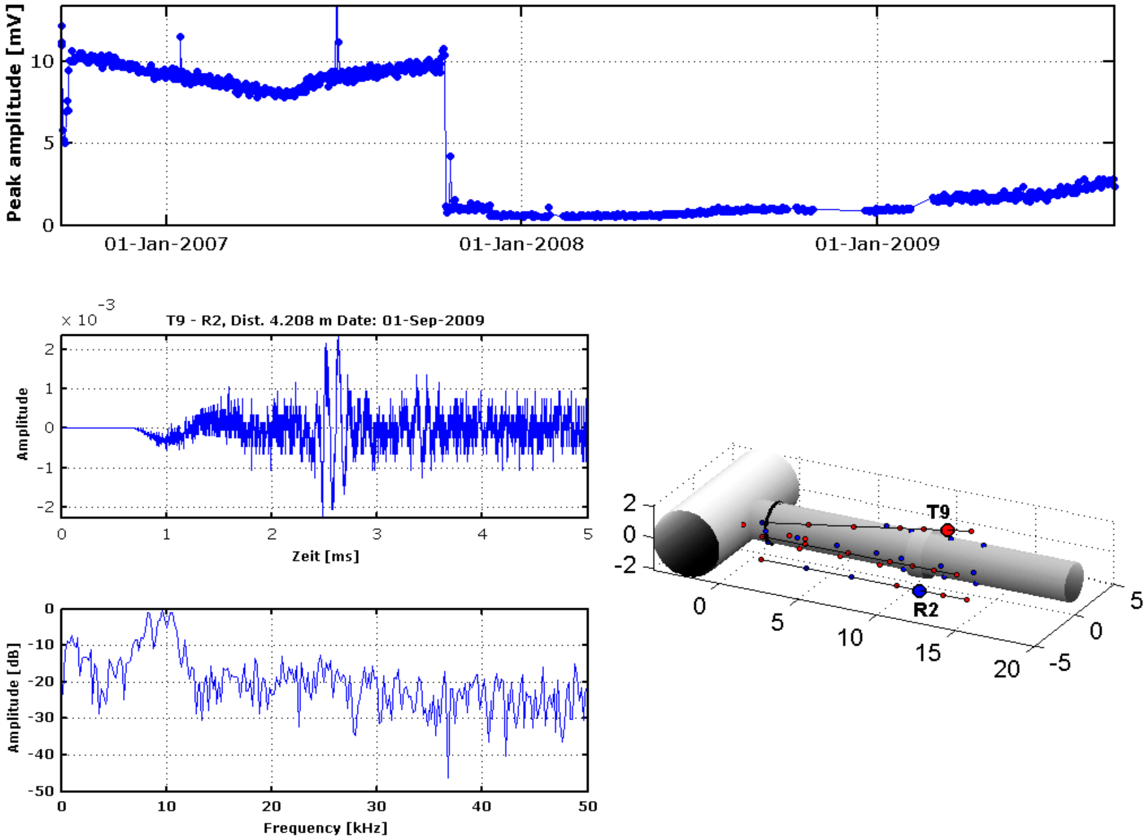

Fig 5-3-4: Evolution of P-wave signals between T9 and R2 from 2006 to 2009, no filtering.

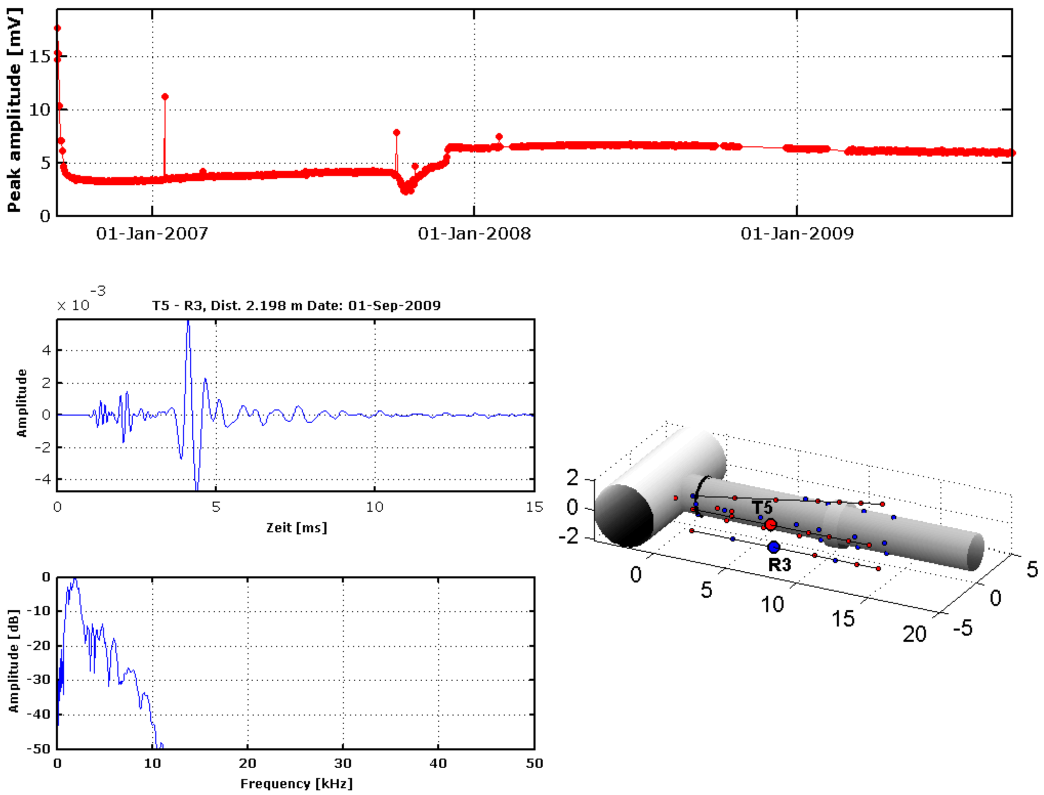

Fig 5-3-5: Evolution of S-wave signals between T5 and R3 from 2006 to 2009, low-pass filter 5 kHz.

Seismic hammer

To have a more pronounced generation of S-waves, an additional source (shear wave hammer) has been designed, and a prototype was available early 2013. Test will be carried out in a dedicated borehole parallel to the PRACLAY Gallery.

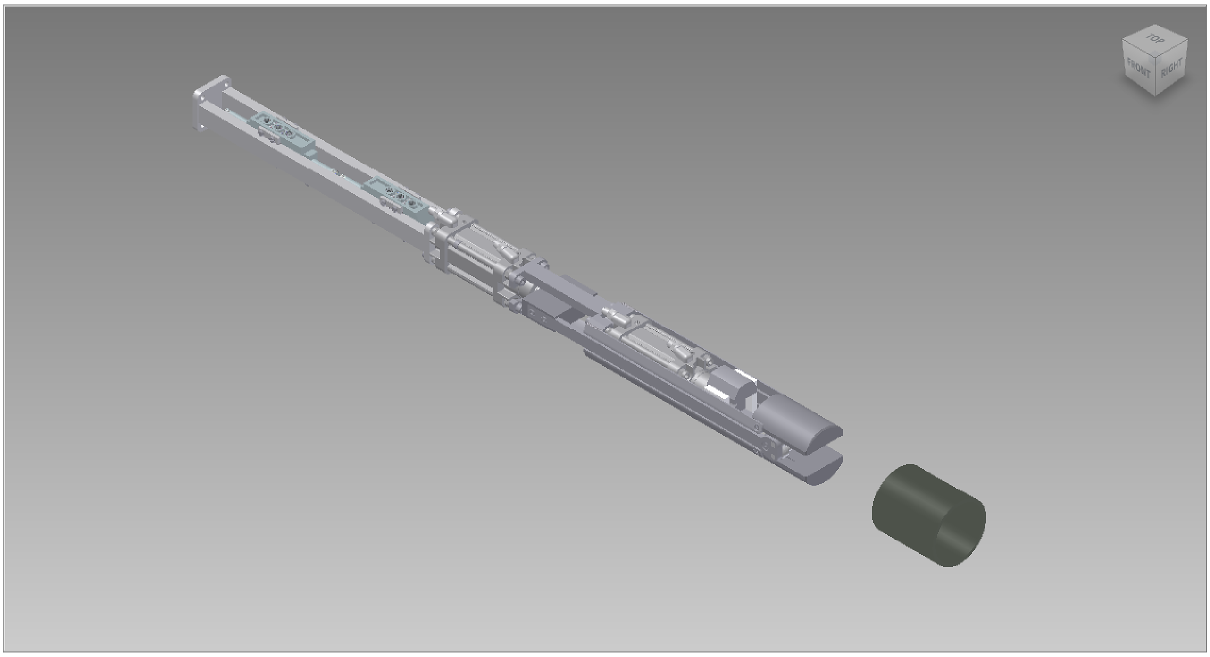

Figure 5-3-6: New S-wave Hammer

The data acquisition (DAQ) system combines micro-seismic transmission and ultrasonic acoustic-emission (AE) measurements. It includes both a digital signal generator and a transient recorder built-in and controlled by an industrial personal computer, as schematically shown in Figure 5-3-7. The sampling frequency is 500 kHz. The DAQ system is accessible via an internet connection and operates fully automatically.

AE monitoring is active from 8 pm to midnight. These measurements run in the frequency range of approximately 1 kHz to 50 kHz, with a high-pass filter set at 1 kHz to filter out the low frequency background noise. The micro-seismic transmitter-receiver measurements run with all appropriate transmitter receiver combinations (Figures 5-3-3) between midnight and 5 o'clock in the morning. Both measurements are performed daily and outside normal work hours to avoid work-related disturbances.

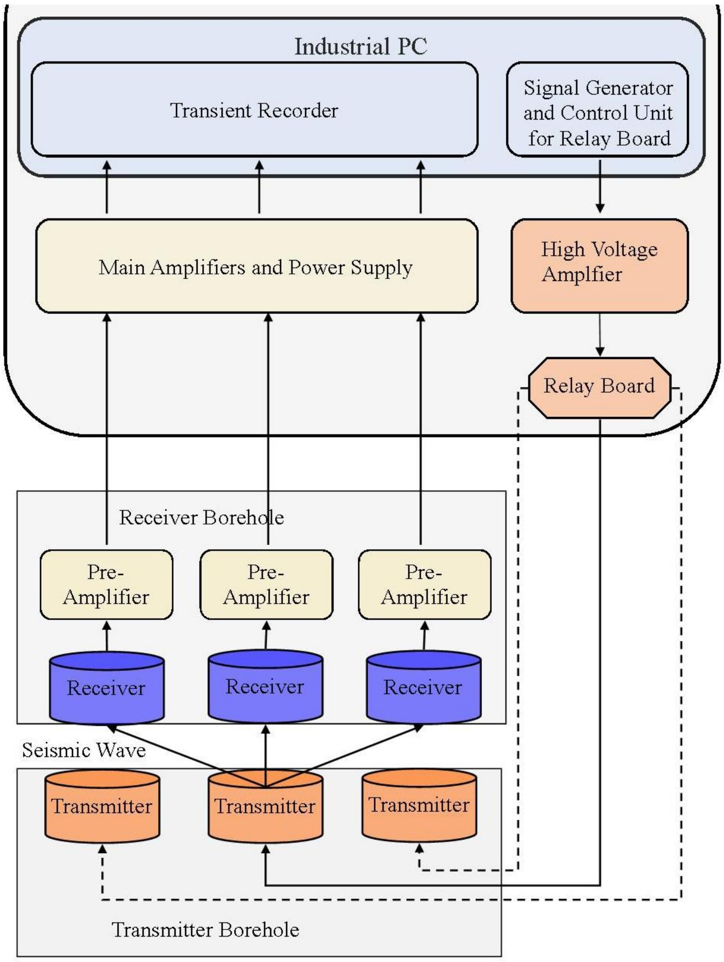

Fig 5-3-7: Data acquisition system.

Monitoring of the Belgian Supercontainer

The Supercontainer is the Belgian reference concept proposed by ONDRAF/NIRAS, for the packaging of HLW and spent fuel (ONDRAF/NIRAS, 2009; 2010). It is based on a multiple barrier system that includes an outer steel envelope, a concrete buffer and a water-tight carbon steel overpack containing one or more waste canisters.

The long-term safety function of the overpack is to contain the radionuclides during the thermal phase, which will last several thousand years. One of the long-term functions of the concrete buffer is to provide a high-alkaline chemical environment that favours the formation of a tightly adhering passive oxide film on the external surface of the carbon steel overpack, which protects the underlying metal. The presence of the oxide film is believed to result in negligible and uniform overpack corrosion rates. In order for the safety functions to be achieved, the concrete buffer should not contain through-going cracks.

In order to demonstrate the feasibility of Supercontainer construction, one half-scale test (HST1) has been performed (Areias et al., 2010) and another is being undertaken in 2013 (HST2). The half-scale tests (Figure 5-3-8) have true diameter scale, but they are limited in height to approximately half of a real Supercontainer.

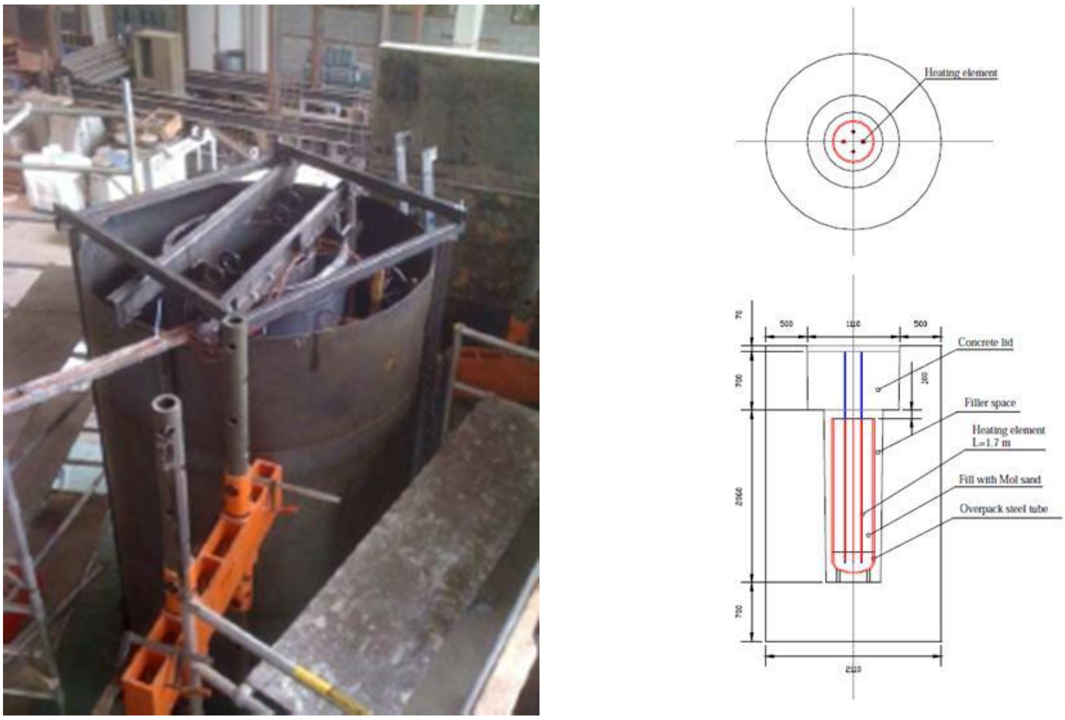

Figure 5-3-8: Setup of the half-scale tests: view of the assembled mould before casting of the buffer (left); schematic view showing the buffer and overpack/heater (right)

The performance of the Supercontainer is being monitored from the outset and will continue in the longer term. Parameters being monitored include overall deformation, shrinkage, corrosion, and moisture content.

Figure 5-3-9: Three different sensors for on-line measurement of the corrosion rate

Also more traditional sensors (vibrating wire and resistive strain gauges, temperature sensors, etc.) are installed – these will serve as a reference for comparison to assess the performance of the different techniques.

Figure 5-3-10: Set-up to test optical fibre compatibility with cast concrete

The second half-scale test is being extensively monitored, as illustrated in Table 3.1.

Table 3.1: Monitoring parameters and instrumentation in HST1 and HST2.

Instrumentation	Parameter	HST1	HST2
Thermocouple	Temperature	X	X
Strain gauges (including vibrating wire gauges)	Strain	X	X
LVDT (Linear Velocity Displacement Transducer)	Displacement	X	X
Anemometer	Wind velocity	X	X
Humidity TDR probe	Moisture content	X	X
DIC (Digital Image correlation)	Onset and evolution of cracking		X
AE (Acoustic Emission)	Crack formation		X
Total pressure sensor	Total pressure		X
Fibre optics	Temperature, axial and radial strain		X
Oxygen sensor	Oxygen flux		X
Reference electrode	Corrosion potential		X
Corrosion sensor	Corrosion rate		X

Monitoring of both of these experiments has partly been undertaken within the framework of the MoDeRn Project, in particular the development and testing of:

- Digital Image Correlation (DIC): DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images. This is often used to measure deformation (engineering), displacement and strain, and is widely applied in many areas of science and engineering, for example Lecompte *et al.* (2009); Lecompte (2007); Sutton *et al.* (2009); and Aggelis *et al.* (2013). This technique could be used to monitor for the onset and evolution of cracks in general and in particular within the supercontainer prior to backfilling, and, should spaces in the repository not be backfilled, over the long term. However, such monitoring needs access to the object being monitored and would need to be developed to be suitable for installation in the small annulus available around the Supercontainer when emplaced in a disposal tunnel or would require changes to the reference design (e.g. use of a larger annulus around the Supercontainer to provide space for DIC monitoring).
- Acoustic Emission (AE) Monitoring: AE techniques are widely used in mining, tunnelling and hydro fracturing projects to monitor crack location, density, development and evolution. AE can track changes in the depth and mode of the cracks in concrete structures (Aggelis *et al.*, 2013) when sensors are located in a 3D pattern. Crack depth

can also be measured by one-sided ultrasonic test (UT) measurements since the travel time of the excited wave increases due to the discontinuity created by the crack along the wave travel path (Doyle and Scala, 1978). Cases that demonstrate the use of AE to monitor the evolution of cracks in concrete include Doyle and Scala (1978) and Robeyst *et al.* (2009). AE could be used to detect micro-seismic activity, and crack location, density, initiation and propagation in concrete. This would require the placement of accelerometers in suitable locations around the emplacement tunnel, most probably in boreholes, but the accelerometers can also be cast directly into the concrete. In the case of boreholes, the potential impact of such boreholes on the containment functions of the near-field rock would have to be assessed before AE monitoring could be considered feasible.

- Corrosion Sensors: Corrosion sensors typically detect metal corrosion through changes in the electrical current of the medium of interest. The corrosion rate can be estimated through measurement of the voltage or current between a reference electrode and the metal being monitored. Corrosion sensors are frequently applied in the field to measure corrosion activity of gas and oil pipelines and offshore structures, and to monitor corrosion activity of embedded reinforcement bars in concrete. Corrosion sensors could be used to undertake *in situ* monitoring of the corrosion of disposal overpacks. This would require emplacement of electrodes and/or excitation currents within the Supercontainer. The impact of these materials on the functions of the Supercontainer components would need to be evaluated before this technique could be considered feasible. An alternative would be to use the corrosion sensors in a pilot facility or sacrificial cell. In addition, the relaying of the information from such monitoring, e.g. using the high-frequency methods described in Section 5.2 would require demonstration.

The half-scale Supercontainer test incorporates approximately 150 sensors to monitor temperature, strain, deformation, displacement, relative humidity, total pressure, corrosion and micro-seismic activity. The test is planned to last approximately 18 months and includes two heating and cooling periods to study the thermo-mechanical properties of the concrete materials used in the Supercontainer.

Approximately half of the monitoring techniques use classical instrumentation such as resistance and vibrating wire strain gauges, thermocouples, linear displacement transducers, time-domain reflectometry humidity probes and diaphragm pressure sensors. The other half use state-of-the-art technologies, including:

- Fibre optic sensors to measure radial, axial and circumferential strain, and temperature (research into fibre optics within the MoDeRn Project is discussed in Section 3.2.5).
- DIC in combination with AE and UT to measure onset and evolution of micro cracks in the concrete buffer and cementitious filler.
- Four types of corrosion sensors are being used in the second half-scale test to monitor the corrosion activity of the carbon steel overpack. These include the use of weight loss coupons cast in the concrete buffer, one technique based on the variation of the linear polarization resistance, one sensor based on the open circuit potential which applies low amplitude, multi-frequency alternating current signals between a reference nickel auxiliary electrode and a sample of carbon steel representing the metal overpack, and finally a technique that measures the instantaneous corrosion using the single sine electrochemical impedance spectroscopy (EIS) method.

5.3.4 Lessons learned

Fibre Optic Sensing

The use of fibre optic sensing reduces eliminates the need for calibration of inaccessible sensors. The results so far show that the fibre optic sensors are capable of quantifying displacements with a resolution of 1 µm, permitting monitoring of very slow movements, typical of the evolution of long-term repository processes. This system will continue to be tested as the PRACLAY experiment continues and the results when the temperature is increased up to 100 °C will help provide information on the durability of fibre optic sensing in a high temperature environment more typical of geological disposal.

Micro-seismic Monitoring

The seismic installation at HADES is providing useful information on the changing properties of the Boom clay around the PRACLAY gallery. The development of the new seismic hammer has helped in the generation of high-energy, low-frequency shear waves.

The results of seismic monitoring to date show that S wave frequencies are mainly below 1 kHz, while P waves show optimum resolution of between 7 and 23 kHz. The evolution of P and S wave velocities in the EDZ around the PRACLAY gallery show continued recovery (self-healing) since construction in 2007. Modelling results of the variation in crack density obtained from the inversion of modelled P-wave transmission velocities confirm the recovery of the EDZ and the self-healing properties of the Boom clay. The seismic monitoring programme will also provide useful information on these changes as the PRACLAY experiment continues.

Supercontainer Tests

The Supercontainer tests continue to provide valuable information on all aspects of the performance and quality of the sensors in general, including improvements in installation, design, robustness and accessibility.

So far, the DIC monitoring in the second half-scale test has demonstrated its value in detecting surface shrinkage, onset of crack initiation, crack propagation and crack width, and displacement and strain fields at different levels across the height of the concrete test cylinder as a function of time.

The main conclusions pertaining to the experience gained with the use of AE in the second half-scale test include its capability to detect phenomena occurring in fresh and early-age concrete such as particle segregation, migration of gas and water during initial stages of curing and setting, and monitoring of the hydration process.

Cracks detected through the use of DIC in combination with AE and UT, have allowed cracks with a diameter of 13 microns to be detected, and the results indicate that DIC in combination with AE and UT can be used to track, in real time, the development, depth and evolution of micro cracks in concrete.

Results from three of the four types of corrosion sensors were not available at the time of writing. However, the sensor based on the single sine EIS method has been tested in laboratory experiments, and has allowed measurement of accumulated corrosion rates and detection of passivation of the surface of a steel sample. It is anticipated that this method will allow measurement of corrosion rates on the order of µm/yr.

5.3.5 Issues for further R&D

The continuation of the PRACLAY programme beyond the end of the MoDeRn project will allow for continuing monitoring using fibre optic sensing and micro-seismic monitoring. The Heater Test will commence once the required level of saturation and swelling of the bentonite seal has been achieved; this phase should assist in our understanding of how robust the technique of fibre optic sensing is to higher temperatures as well as providing information on the impact of such heating on the disposal cell construction and the surrounding geology.

Regarding distributed sensing, the optical fibre monitoring techniques show a lot of potential. Optical fibre technology can be considered as mature – and fibres are now omnipresent in communication applications. When used for repository monitoring however, calibration appears to be the most relevant issue. In theory, high accuracies with elevated spatial resolution (typically far better than a metre) can be obtained, but this requires a comprehensive knowledge of processes that affect the response of the fibre to the target parameter. For the combined strain/temperature principles, distinguishing between both parameters can be problematic, as a stress-free installation usually cannot be guaranteed.

Research is currently very active in this domain, and efforts are underway to apply a hybrid Brillouin/Rayleigh system in order to try to obtain both temperature and strain from a single fibre.

There are many designs for the outer coatings of fibres. These should be adapted to the environment to offer sufficient ruggedness (e.g. strong enough to resist installation manipulations), without affecting the sensing characteristics. The performance of optical fibres will depend in part on the way it is installed. Further understanding of installation procedures is therefore required, not only to avoid damages of fibres and connectors during installation, but also to have confidence in the measurement results.

The micro-seismic monitoring programme will also continue throughout the PRACLAY programme and will provide valuable learning on the use of this technique in monitoring changes. Continued experience in the recently developed seismic hammer will enhance the ability to progress effective S-wave monitoring and continue to provide information on changes to the EDZ as the heating experiment progresses.

The most important technical issues regarding supercontainer monitoring technologies that still remain to be addressed before these techniques can be implemented in a geological repository are those related to accessibility, data transmission, power requirements and the potential impact of the monitoring equipment on the safety functions of the barriers being monitored. Future research is needed to address these issues.

5.4 Long range low-frequency wireless data transmission

This research programme has been developed to test and demonstrate the feasibility of wireless data transmission from a deep geological disposal to the surface in the post-closure phase by low frequency magneto-induction techniques. The use of low-frequency fields overcomes problems with strong signal attenuation by solid media that occur with high-frequency data transmission. In magneto-induction, magnetic fields are generated by a loop antenna that propagates through the host rock. This provides a potential method for transmitting signals through plugs, seals and dams, between different parts of a repository or from the repository to the surface.

The signal attenuation, by interactions with the transmission medium at low frequencies, depends on the electrical conductivity of the media through which the signal is transmitted, with lower conductivities favouring signal transmission: high electrical conductivities induce more eddy currents and secondary fields, which attenuates the primary field. This is of importance when considering the application of this technology because the electrical conductivity of geological media can vary significantly. Typical values for electrical conductivity range from µS/m to mS/m in rock salt and crystalline rock, and from mS/m to S/m for argillaceous rocks. The water-filled porosity of a geological media has a significant influence on the electrical conductivity (ground water conductivity is about 0.5 S/m).

Tests have been conducted on the wireless transmission of signals and data over large distances through geological media using low frequency magneto-induction techniques. This should help to assess the feasibility of long-term wireless data transmission from an underground repository through the host rock and the overlying geosphere to the surface, which could have particular application for monitoring post-closure.

This work has been carried out in the HADES underground facility located at Mol, Belgium, at 225 m depth in an 80 m thick layer of Boom Clay. The work has been managed by Nuclear Research and consultancy Group (NRG) of The Netherlands.

A more detailed report on this work has been published within the MoDeRn Project (MoDeRn, 2013g and MoDeRn, 2013n)

5.4.1 Objectives and rationale

In the event that monitoring of the underground disposal is required after closure, an autonomous monitoring system that enables the wireless transmission of data from the repository to the surface would be required. To transmit data over a few hundreds of metres through geological media, only a limited number of principal techniques are feasible. Within the MoDeRn project, tests have been conducted 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 main objective of the experiments performed is to demonstrate the principal feasibility of data transmission in the post-closure phase. The main focus of the research is to characterize and optimize the energy use of this technique within the specific context of post-closure monitoring. Due to the high electrical conductivity of the Boom Clay and the overlying aquifers, these layers are expected to attenuate the magnetic fields more strongly than other host rocks e.g. granite, salt rock or Opalinus clay. The experiments will also help understanding what external factors (e.g. background noise) may need to be taken into account when using this technique.

5.4.2 Key programme challenges

For the wireless transmission of data, high-frequency electromagnetic waves are used in many applications. Electromagnetic waves can be transmitted easily over larger distances in air, but the presence of solid objects is known to potentially impede the wave propagation. When *in situ* monitoring of a geological radioactive waste disposal facility is continued in the post-closure phase (i.e. when the access shaft is closed), data acquired by the underground monitoring system need to be transmitted wirelessly over longer distances (>100 m) to the surface. For the wireless transmission of data between different deep geological repository sections or between the repository and the surface, the electrical conductivity of the geological media can cause significant attenuation of the signal and challenge the feasibility of transmitting high frequency waves.

As with high-frequency data transmission, application of such monitoring faces technical challenges, including optimisation of the energy efficiency achievable by the technique, the provision of energy for generating the signal, the use of suitable modulation and error detection methods for a certain frequency range, and the long-term durability and reliability of components of the system. Data transmission in the low-frequency spectrum also has the added challenge of handling interference with non-Gaussian pattern (e.g. pulses, energy bursts).

The electrical conductivity of geological media can vary to a large extent, from µS/m to mS/m range for rock salt and crystalline rock, and mS/m to S/m range for argillaceous rock. The water-filled porosity of a geological media has a large influence on the conductivity (ground water conductivity is about 0.5 S/m). In case of the Dutch generic disposal concept in argillaceous rock, the repository would be situated in Boom Clay, a host rock with relevant water content (35-40%). Above the layer of Boom Clay, highly conductive sandy aquifers are situated, which also limits the application of high frequency radio waves.

5.4.3 R&D to address challenges

The experimental set-up utilizes a loop antenna for the transmitter that has been matched to the existing infrastructure of the HADES URL. Between 2010 and 2013, NRG carried out several experiments at HADES in order to test the technical set-up and to characterize the propagation behaviour of the geological medium and the local background noise pattern. Potential transmission channels have been identified up to 1.8 kHz and data transmission has been demonstrated at several frequencies, with data rates up to 100 bit/s and bit error rates <1%. A mathematical model description that includes the most relevant characteristics of the transmitter, transmission path and receiver has been developed which enables the analysis of possible options to optimize the design. With respect to the energy-efficiency, model calculations and results shown that data transmission over larger distances through the subsurface is a feasible option. To support predictions on the energy need per bit of transmitted data, several experiments have been performed at the HADES URL and an alternate location.

To transmit monitoring data from a radioactive waste repository to the surface, a number of specific requirements and boundary conditions for the application of wireless techniques can be defined:

- fixed antenna locations exist and the transmission path and distance are known;
- the transmission properties of the host rock and overburden are relatively constant and can be determined;

- a large range of antenna geometries and sizes can be realized within a disposal concept when a horizontal loop-antenna set-up is selected;
- localized sources of interferences, both underground and on the earth's surface, can be eliminated or reduced;
- no specific timeframe for data transmission is necessary;
- requirements on transmission speed are low;
- an accurate transmission of data is essential; and
- the supply of energy in a repository would be limited.

For the transmission of monitoring data out of a repository, a low energy need was assumed the most important design criterion for the case of long-term monitoring of a radioactive waste disposal in the post-closure phase. Irrespective of the energy supply provided, (e.g. by long-lasting batteries; techniques that convert thermal, chemical or radiation energy in the disposal facility; or wireless energy transmission from the surface), based on the current state of technology, it is reasonable to assume that the energy supply will be a limiting factor. The amount of energy necessary to transmit monitoring data in the post-closure phase depends mainly on two factors:

- energy use per bit of transmitted data; and
- the amount of data that need to be transmitted.

The energy use per bit of data can be improved by analysing the relevant components of the transmission chain and refining the transmission equipment and set-up. The amount of data that will be sent can be decreased by careful consideration of the data need, e.g. the necessary interval of data transmission, the precision of the transmitted data, the coding of the data, and the kind of information that need to be transmitted in order to monitor the repository's evolution. Two example calculations may give a first impression of the order of magnitude of data that need to be transmitted:

- if readings of 100 sensors are transmitted every month for 30 years with a precision of 0.1% and 30% redundancy by error detection and correction codes, a total amount of about 60 kB of data will be transmitted;
- if readings of 1000 sensors are transmitted every week for 100 years with a precision of 0.1% and 30% redundancy by error detection and correction codes, a total amount of about 8.5 MB of data will be transmitted.

These examples can be used for a first rough estimate of the energy efficiency that has to be achieved: when powered e.g. by the energy equivalent of a conventional car battery (500 Wh), assuming 50% of the energy is actually used for transmission, in the first example an energy need of less than 2 Ws/bit must be aimed at. In the second example, data need to be transmitted with less than 0.01 Ws/bit. When energy is supplied by other sources (e.g. nuclear batteries, Peltier elements), then the necessary energy efficiency of the applied technology, can be specified accordingly.

5.4.4 Experimental configuration

With respect to the electrical conductivity of the transmission path, conditions at the HADES URL are quite comparable to what is expected for the generic Dutch disposal facility in Boom Clay, although the depth of the HADES URL is about half of the generic depth for the Dutch disposal design (225 m vs. 500 m). To be able to extrapolate the results of the experiments performed in Mol to a depth of 500 m, a proper characterization of the frequency-dependent field propagation behaviour was performed.

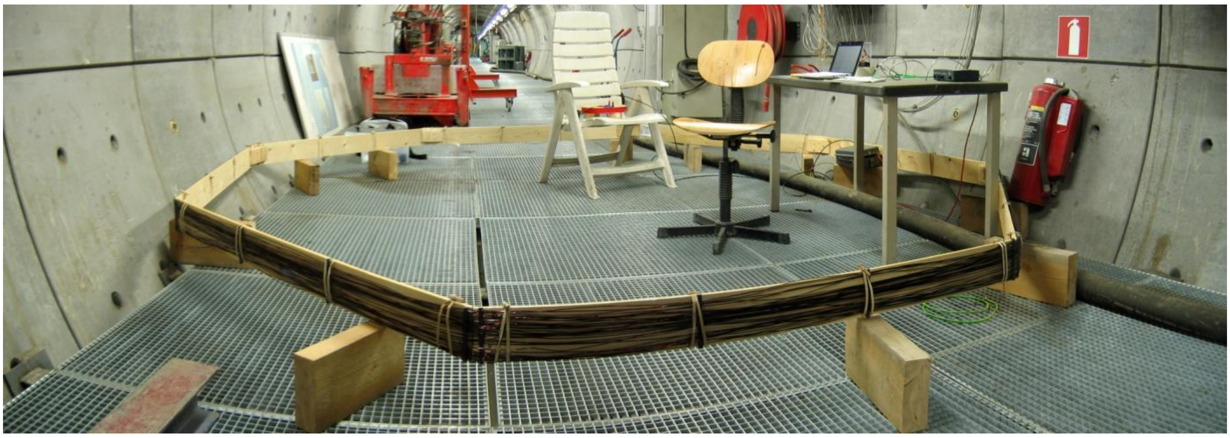

Fig. 5-4-1: Transmitter antenna ECN-1 in the HADES URL

With respect to the boundary conditions defined earlier, the experimental conditions at Mol are not optimal with respect to three features:

- the size of the transmitter antenna is limited by the diameter of the HADES URL (Fig. 5-4-1), leading to an antenna aperture far below optimum;
- due to the presence of several on- and off-site power-lines, strong interferences exists on the surface above the HADES URL; and
- the experimental work was performed during day time, leading to additional transient interferences (e.g. by passing cars, operation of the shaft winding facilities) that cause difficulties in the statistical analysis of data-transmission results.

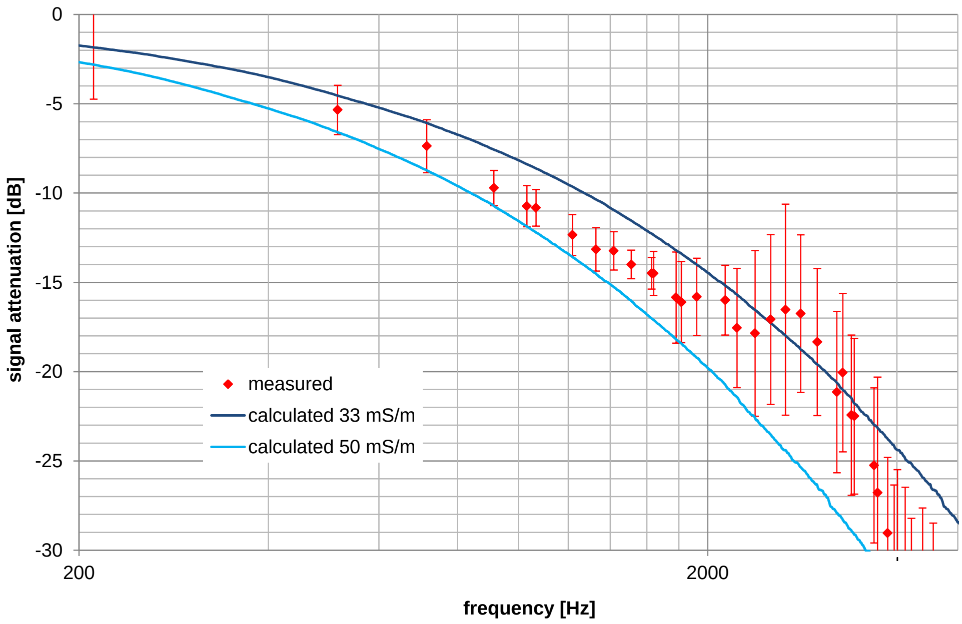

Figure 5-4-2: Measured and calculated signal attenuation by the geological medium (r = 225 m) between 200 Hz and 5 kHz. Error bars represents the measured standard deviation. Note that measured values above 2.3 kHz are either transmitted signals or background noise or a combination of both.

A first estimation of the frequency range that has to be considered for the signal and data transmission experiments lead to a range of 200 Hz to 5 kHz. Figure 5-4-2 shows the frequency-dependent attenuation by interactions with the geosphere. Evaluating these and other factors, for the data transmission experiments, a frequency range between 1.0 kHz and 1.7 kHz was chosen.

Before starting experimental work, all components of the transmission chain were analysed with respect to the energy efficiency of the design, and in several iterative steps, equipment and set-up was modified in order to anticipate the local circumstances in the HADES URL and at the surface. To overcome limitations imposed by strong interferences of the power network present at the Mol site, additional experiments were performed at a recreational area close to the NRG site in Petten, The Netherlands. Although these tests were limited to surface-surface transmissions, they provided valuable information by demonstrating the sensitivity of the receiver.

In 2010, the principal experimental set-up and experimental boundary conditions have been established: first, the necessary hardware was designed and assembled and a proof-of-principle experiment was executed in the Netherlands to demonstrate that the transmitter-receiver set-up was performing as expected. In 2011 and 2012, the site-specific magnetic background noise pattern at the surface in Mol was recorded and analysed as a function of time and frequency, and from this data, the frequency-dependent signal attenuation by the geological medium between the HADES URL and the surface was determined (Fig. 5-4-2). Those experiments have delivered sufficient information in order to proceed to the final step, performed in 2012 and 2013: the selection of a suitable data transmission channel and the demonstration of data transmission from the HADES URL to the surface, including testing of different data modulation options and methods in order to optimize the energy efficiency.

5.4.5 Results of demonstration activities

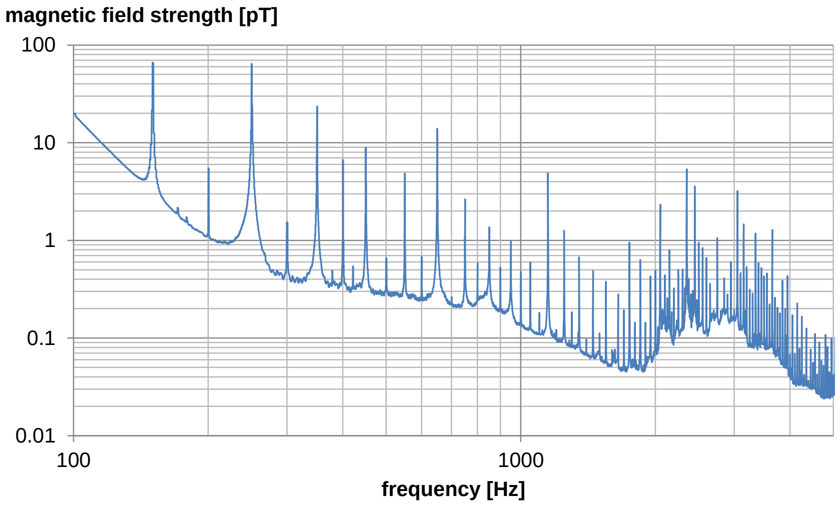

Fig. 5-4-3: Magnetic noise pattern at the surface in Mol

Figure 5-4-3 shows the magnetic field strength recorded at the surface in Mol, on top of the HADES URL. As a result of a large number of harmonics of the 50 Hz power network, strong interferences are visible over the whole of the frequency range envisaged for data transmission. The radial field component was larger than expected from approximation function; however, these approximation functions are only valid under near-field conditions which in this case are clearly exceeded above 500 Hz (i.e. skin depth $\delta > 225$ m).

The strong peaks, depicted in Figure 5-4-3, also affects the bandwidth for data transmission: generally, data transmission techniques make use of an undisturbed part of the spectrum, i.e. data rates will be limited to less than 50 sym/s. Comparison with the noise pattern of a recreational area close to the NRG-site in Petten, The Netherlands, show that much lower background levels are achievable (data not shown). Technical improvements of the receiver realized during the project resulted in higher receiver sensitivity and allowed the detection of magnetic fields of 10 fT. The increased receiver sensitivity could be demonstrated in and at the recreational area, but were of less relevance in Mol under the conditions as depicted in Fig. 5-4-3, because the background noise at Mol was clearly the limiting factor.

Figure 5-4-4 shows the reception of signals transmitted from the HADES URL to the surface. Signals up to 2.2 kHz can be received, with the most favourable SNR located between 1.0 and 1.7 kHz. It should be noted that without interference, optimum data transmission frequencies may be higher. Applying the electrical conductivity σ of the transmission model to the measured data resulted in a best fit value of 50 mS/m, which is close to the 33 mS/m reported by EURIDICE based on average conductivity measurements of borehole cores (see also Fig. 5-4-2).

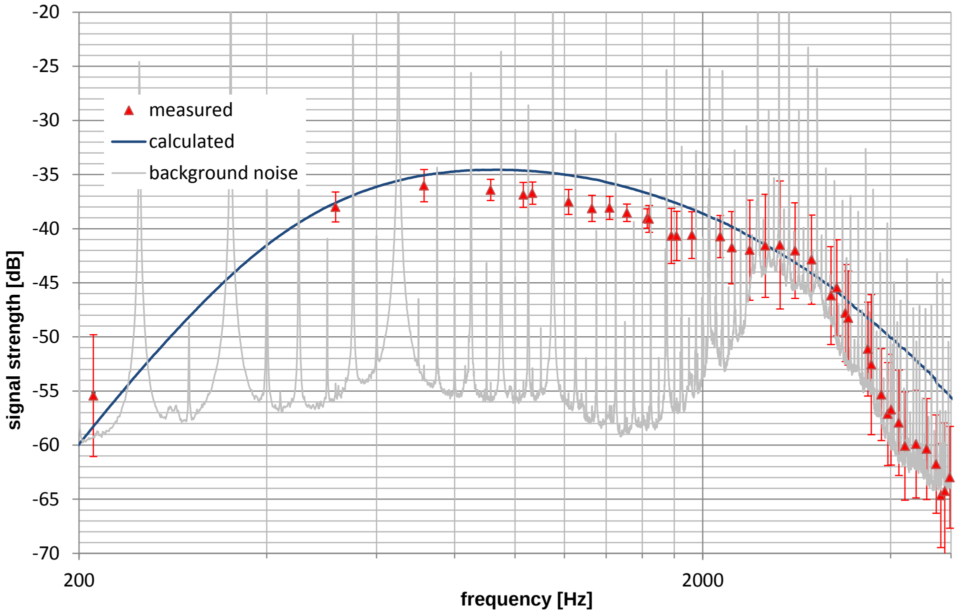

Fig. 5-4-4: Measured and calculated signals strengths, and averaged background noise level recorded at the surface in Mol on 8-8-2012 (σ = 33 mS/m, r = 225 m). Error bars represents the measured standard deviation.

After having acquired sufficient data on the propagation behaviour of the underground and the local noise pattern, data transmission experiments were carried out. First experiments demonstrated the ability to transmit data from the HADES URL to the surface at two frequencies with data rates up to 10 bit/s and bit error rates (BER) below 1%. Table 5-4-1 summarized a first set of indicative results. It should be note that the length of the experiments was too short to obtain meaningful statistical conclusions, i.e. errors are not randomly distributed but could partially attributed to single events (e.g. car passing by). Table 5-4-1 gives an overview of the best results achieved. Extrapolation of the results of additional measurements performed in a surface-surface configuration under comparable conditions in a recreational area in The Netherlands show that with weaker local interferences, data transmission from the HADES to the surface must be possible with a few mWs/bit (data not shown).

Table 5-4-1: Results of data transmission experiments.

Frequency (Hz)	Data rate (sym/s)	Signal level (dB)	Power (Ws/bit)	BER* (%)
1627.15	10	0 -3 -6 -9	19.0 9.5 4.8 2.4	0 0 0.2 0.2
1613.5	20	0	1.0	0.5
1675.00	25	0	1.3	0.4
1523.81	30	0	4.2	0.7
1523.81	30	0 -3	4.2 2.1	0.4 0.5
1573.77	30	0 -3 -6	7.3 3.7 1.8	0 0.06 0.06
1613.45	90	0	1.9	0.4
1606.70	60	0	3.3	0.06
1606.70	100	0	2.0	0.2

* Note that number of transmitted data bits is too small to allow a proper statistical evaluation (about 25'000 bits)

5.4.6 Lessons learned

The experiments summarized in the previous section clearly demonstrated the ability to transmit data through approximately 225 m of highly conductive geological medium, even under unfavourable experimental conditions as present in Mol (limited space for transmission antenna and large local interferences). This raises confidence in the extrapolation of experimental result to the "real case". The next step was to analyse the energy need for a generic disposal concept and to identify potential options to increase the energy-efficiency. A mathematical model has been developed that describes the expected signal strength on the surface on basis of the most relevant characteristics of transmitter, receiver and transmission path. The model is used to analyse the complex interactions of different parameters, and is used to design an optimized set-up for data transmission and to estimate minimum energy demand for signal transmission.

Several calculations have been performed in order to design the most energy-efficient set-up for different situations. An overview of energy efficiencies for different situation, based on measurements and model calculations is summarized in Table 5-4-1.

Table 5-4-1: Demonstrated, extrapolated or estimated energy need for data transmission for different situations.

Set-up	Achievable Data Rate	Energy per Bit of Data	Description
HADES URL at 225 m, small antenna (*r* = 1.85 m)	≥100 sym/s	1000 mWs/bit	demonstrated at HADES URL
HADES URL at 225 m, small antenna (*r* = 1.85 m), assuming no interference from power network	≥100 sym/s	1.4 mWs/bit	demonstrated in surface-surface configuration and extrapolated to HADES URL conditions
Dutch generic reference concept in Boom Clay at 500 m, large transmitter antenna (*r* > 125 m)	>30 sym/s	<1 mWs/bit	conservative estimation based on model calculation
Dutch generic reference concept in rock salt at 800 m, large transmitter antenna (*r* > 200 m)	>40 sym/s	<1 mWs/bit	conservative estimation based on model calculation

In conclusion, the demonstration results and quantitative analyses performed shows, that wireless data transmission post-closure is feasible for the particular case of the generic Dutch disposal concepts in Boom Clay and rock salt, and would be expected to be applicable for other similar disposal concepts, with an estimated energy need of <1mWs per bit of transmitted data. Some additional confidence in the technology could be gained by performing additional experiments that allows the deployment of a loop antenna of a relevant size (i.e. with a radius comparable to the transmission distance), which wasn't possible at the HADES URL.

5.4.7 Issues for further R&D

The experimental and theoretical results gained by NRG, as part of the European 7th framework project MoDeRn, demonstrated that data transmission through 225 m of a geological medium is feasible, even in case of a highly conducting medium as present in Mol. The amount of energy necessary to transmit data to the surface is within expectation, although due to the local conditions in Mol (limited space in the underground facility, strong interference above ground) the capability to demonstrate the expected efficiency of the technique was limited.

However, there are several areas that need to be considered and/or developed:

- Uncertainty over the amount of data that may need to be transmitted post closure and the duration of post-closure monitoring. In addition, closer analysis of sensor signal is required to recognise the difference between potential sensor failure and unexpected evolutions (MoDeRn, 2013m) - evaluation should be made of whether it is necessary to transmit primary sensor signals, in which case the amount of data to be transmitted would be much higher. If analysis of sensor signals can be performed (automated) in the subsurface facility prior to data transmission, it would be sufficient to send the processed numerical outcome, leading to much lower amounts of data to be transmitted.

- Several techniques for continuing to provide electrical power over extended periods of time (several decades) have been suggested but there is no mature technology available at this moment. Further research is therefore required.
- Additional work is required to provide information on the long-term durability/reliability of components of transmission system. This technique has been developed using an experimental set-up and the real application will require development of durable components and system, particularly with respect to the reliability of underground transmitters.
- The frequency range used is vulnerable to natural and man-made interferences, it is therefore important to understand the impact of sporadic loss of data and the potential for countermeasures, recognising the balance between system simplicity and data needs.
- Consideration needs to be given on how to integrate the data transmission system with other monitoring components, including:
  1. Whether data should be transmitted on demand or at predefined intervals;
  2. How energy distribution should be organised and how efficient ‘hibernation’ states can be achieved;
  3. How (different) wireless techniques on different scales can be coupled, and energy supply of these units in the pre- and post-closure phase can be managed.
- The advantages of providing a bidirectional data-link between the disposal and the surface should be considered, recognising the increased complexity of the monitoring system.
- This technology identifies opportunities for data transmission after closure; further analysis of the potential applications should be considered to help focus development requirements.

5.5 Disposal cell Monitoring Systems

This monitoring demonstration is based on a mock-up high-level waste disposal cell. The aim of this experiment was to establish the capacity to conduct integrated monitoring activities inside the disposal cell; on the cell metallic liner; and in the near-field, as well as to assess the capability of the monitoring to withstand construction and liner emplacement procedures. This experiment was realized in Bure Underground Research Laboratory in France in the context of Andra's experimental program.

A more detailed report on this work has been published within the MoDeRn Project (MoDeRn, 2013h and MoDeRn, 2013n)

5.5.1 Objectives and rationale

After having concluded a feasibility study of deep geological disposal for high-level and long-lived radioactive waste in 2005, Andra was charged by the Planning Act n°2006-739 to design and create an industrial site for geological disposal called Cigéo which must be reversible for at least a century. Within the framework of this geological repository project, the observation and surveillance (or monitoring) program must fulfil the knowledge required to operate the disposal facility and maintain reversibility, structured according to steps of progressive construction, emplacement and closure of disposal cells. This stepwise process also allows for the progressive updating and optimizing of the design for future repository components. It also considers potential retrieval of some or all of the emplaced waste. Observation and surveillance also contribute to the safety analyses during operations and after closure.

The French disposal concept for high-level, vitrified waste provides for horizontal, steel-lined, small diameter disposal cells. To address the knowledge requirements referred to above, some of these disposal cells may be selected for in situ monitoring during construction, operation, and the initial closure steps.

There are several challenges to be faced in instrumenting disposal cells. To address these challenges, specific tests and large scale experiments in underground research laboratory have been progressed by Andra. This mock-up high-level waste disposal cell provided the possibility to test and demonstrate such monitoring systems, which has been specially designed to survey the hydromechanical behaviour of the experimental disposal cell.

5.5.2 Key programme challenges

The monitoring approach, defined in the MoDeRn project planning, calls for instrumentation of both the near-field (sensors in boreholes) and the cell liner, to a monitoring system design intended to provide comprehensive data on the thermo-mechanical evolution of the cell and its near-field. The main goal 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.

From a scientific and technical point of view, this demonstrator has the following key objectives:

- To instrument the void space between casing and rock to determine the kinetics of saturation of the annular space and its possible influence on the mechanical behaviour of the casing;
- To evaluate the potential for robust sensor and wiring by testing the feasibility of using optical fibre instrumentation to monitor the overall thermo-mechanical behaviour of the casing;
- To complete the study of the hydromechanical impact of excavation of a cell;
- To monitor near-field hydraulic pressure evolution through vibrating wire technology; and
- To detect and monitor the mechanical behaviour of a 40 m-long casing in relation to the loading applied by the rock.

5.5.3 R&D to address challenges

Typical requirements for sensors intended for future use in a repository include: the longevity of expected monitoring (without real possibility for access to maintain equipment, except by robotic devices); and a high level of required confidence in signal reliability. To function reliably over such a long period of time in such a harsh environment, without access for maintenance presented substantial challenges for most available monitoring equipment, and thus motivated specific R&D to be carried out before this monitoring demonstrator. For example, temperature and strain distributed sensing by optical fibre sensing (OFS), based on Raman, Rayleigh and Brillouin scatterings, have been qualified by Andra through diverse laboratory and field tests.

In order to reach prior objectives of the in situ monitoring demonstration, the instrumentation program included the following measurements:

- The measurement of pore pressure, temperature and displacement around the periphery of the cell in order to determine the hydro-mechanical impact of the excavation;
- The measurement of the hydric conditions (relative humidity and temperature) and of the pressures of any possible water present in the annular space;
- The installation of optical fibres on the internal surface (measurement of deformation and of temperature) and on the external surface (measurement of deformation) of the casing so as to monitor its overall thermo-mechanical behaviour and to detect any possible falls of ground of argillite;
- The measurements of local strain and convergence of the casing so as to determine the way it will be loaded by possible water pressure and/or rock pressure;
- The measurement of the excavation parameters (speed of progress, force of thrust, etc.): on the one hand to estimate the performance and the limits of the method of excavation and, on the other hand, to help to interpret the measurements of the displacement of the rock on the periphery of the cell;
- The measurement of the geometrical characteristics of the cell by a 3D scan.

Some of the measurements planned for this mock-up thus presented some scientific and technical challenges, mainly the feasibility of monitoring in situ using optical fibre sensors (OFS) and pore-water pressure sensors (PWPS) through vibrating wire technology in low permeability argillites. Based on a thorough analysis of available state-of-the-art technologies, Andra has adapted available sensors, when necessary, to meet the technical requirements for monitoring equipment to be used in the repository. Andra has specified a multi-stage qualification procedure, including a careful selection regarding commercially-available technologies, which compared specifications against needs and requirements. If they did not match, internal developments were conducted. Then, various laboratory tests, in controlled conditions, were launched: (i) on the sensing chain alone, and (ii) with sensor embedded in the application material (iii) outdoor test to evaluate influence of uncontrolled parameters (iv) metrological evaluation in order to ensure that calibration procedures are applied to the measurement performance and thus to develop reference sensors as a basis for evaluating possible long-term drift (v) radiation tolerance evaluation.

5.5.4 Experimental configuration

In order to reach the objectives defined above, the excavation programme provided for the creation of a cell with casing over a length of 40 m (the casing and the annular space at the head of the cell being leak-tight), orientated in the direction of the major horizontal stress. The instrumentation of the casing was carried out by Egis Géotechnique in October/November 2011. Casing elements no. 3, 8, 13 and 17 were instrumented (Figure 5-5-1 and 5-5-2).

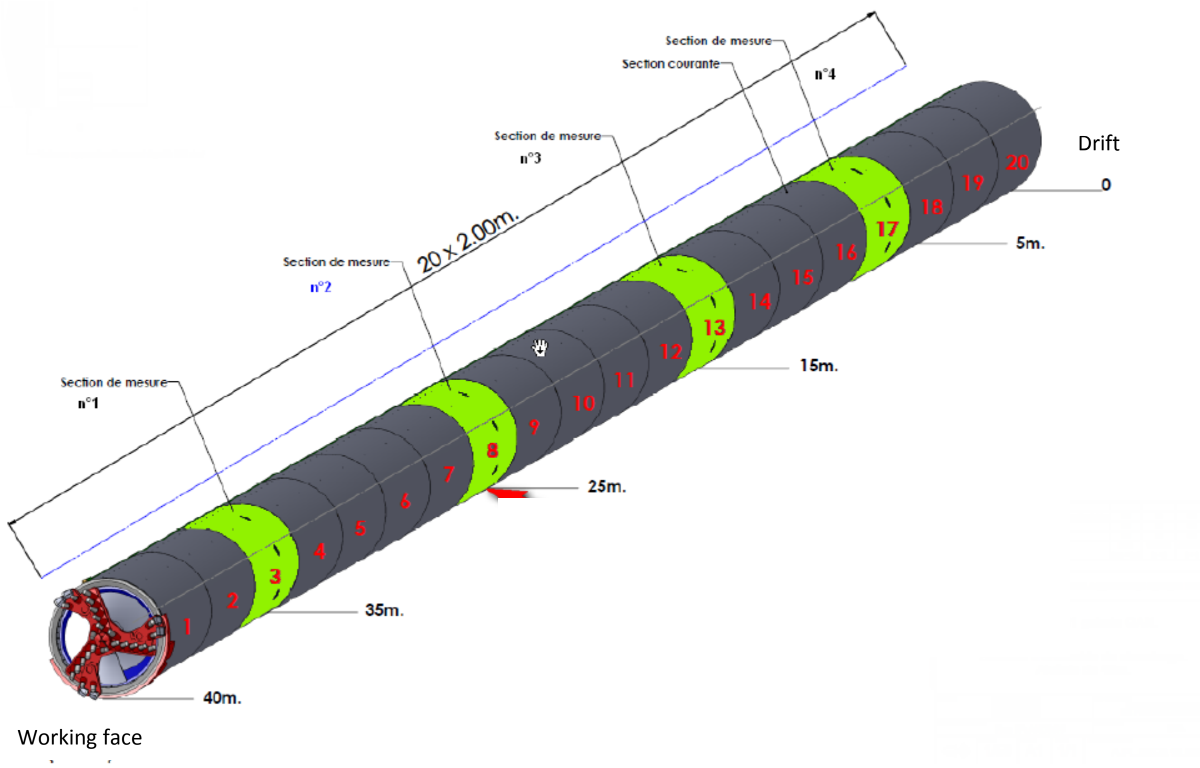

Figure 5-5-1: Location of the 4 instrumented casing elements (in green) of the casing of the cell CAC1601

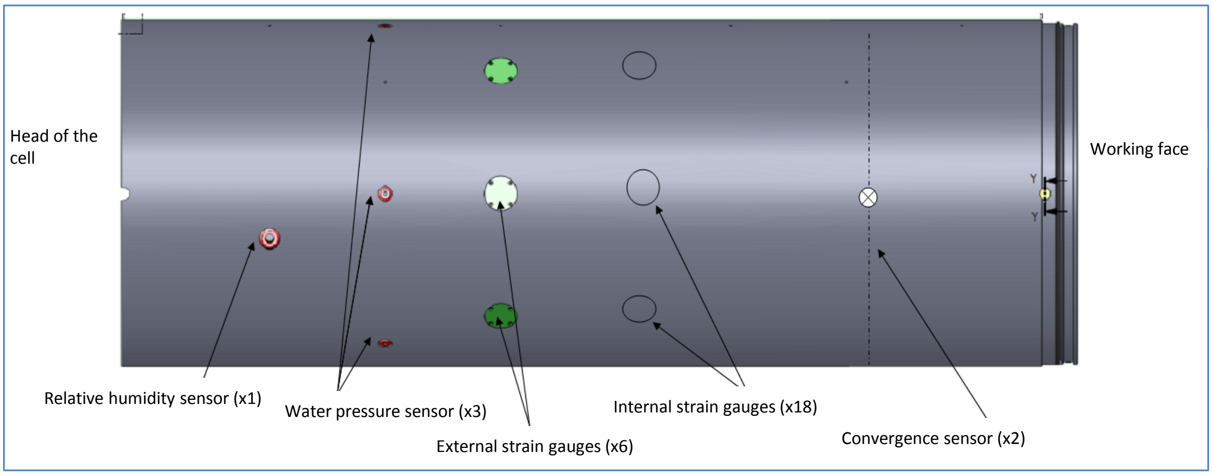

Figure 5-5-2: Location of the sensors on an instrumented casing element

Each of the 4 instrumented casing elements was equipped with the following sensors:

- 18 strain gauges on the internal surface and 6 on the external surface, so as to measure:
  - The local internal deformation of the casing element in 6 corner positions and in 3 directions (longitudinal, circumferential and at an angle of 45º);
  - The local external deformation of the casing element in 6 corner positions and in an ortho-radial direction;
- Two displacement sensors in order to measure the convergence of the casing in the horizontal and vertical directions;
- One relative humidity and temperature sensor in order to measure these two values in the casing/rock annular space.
- Casing elements no. 3 and 17 were also equipped with 3 pressure sensors in order to measure the pressure of any possible water found in the annular space from 3 corner positions. The casing was equipped throughout its length with 4 optical fibres;
- An external fibre to measure possible falls of break-outs after excavation;
- Two internal fibres to measure the temperature profile throughout the length of the casing;
- One internal fibre to measure the deformation profile throughout the length of the casing.

Only the stress gauges were placed on the casing elements before excavation. All the other sensors were put in place either during (for the external optical fibre) or after excavation by human intervention inside the cell.

5.5.5 Results of demonstration activities

Saturation of the annular space

The relative humidity, temperature and water pressure sensors were screwed into a projecting thread (through the casing element) which was made watertight by use of a flat seal.

A progressive saturation of the annular space could be observed, with relative humidity reaching 98% after 300 days in the 3 sections furthest from the gallery (between 15 and 35 m). In the case of the section nearest the gallery (at a distance of 7 m), the relative humidity started to fall after

150 to 200 days. This behaviour can be linked to the evolution of the temperature in the annulus, which, at a distance of 7 m, continues to be influenced by the evolution of the temperature in the gallery. Since the annular space is not yet saturated, no water pressure has been measured to date.

Deformation of the casing

The variation in the diameter of the casing in the horizontal and vertical directions as measured on each of the 4 instrumented casing elements shows a convergence in the horizontal direction and a divergence in the vertical direction. This behaviour is consistent with previous measurements performed on cell demonstrators. The casing has been undergoing deformation ever since measurements started, i.e. at the very latest 1 month after excavation (the time required to install instrumentation). The initial annular space (40 mm over the diameter) between the rock and the casing has closed in less than a month, in the horizontal direction. Since the casing continues to be more and more out-of-round, the clearance in the vertical direction has not yet closed after over 300 days.

Local strain is measured on the internal and external surface on each instrumented casing element, and is monitored from 6 corner positions. The gauges were glued to sheets of 0.3 mm-thick steel, themselves welded at the bottom of spot facings onto the casing. The internal and external sheets are spread out on either side of an internal circumference slot, designed to receive the cables for the gauges. Their respective depths are 7 mm (internally) and 10 mm (externally), and their role is to protect the gauges and their electronic systems during excavation work. (Figure 5-5-3) shows a view of an instrumented sheet, welded to the bottom of a spot facing on the internal surface.

Figure 5-5-3: Instrumented sheet welded to the bottom of an internal spot facing and to which stress gauges have been attached (with 3 directions of measurement) together with their electronic components

The maximum values attained on the internal surface did not exceed 300 µm/m as absolute values, despite local weakening of the casing by the spot facings. On the external surface, the maximum values attained are perceptibly higher, partly because of deeper spot facings (10 mm, or half the thickness of the structure). After 300 days, the casing is weakly loaded ($\sigma\theta\theta < 100$ MPa on the internal surface and at the bottom of the spot facing).

The mechanical signatures of the casing for each instrumented section are presented in Figure 5-5-4. These constitute the polar display of the evolution of circumferential strain.

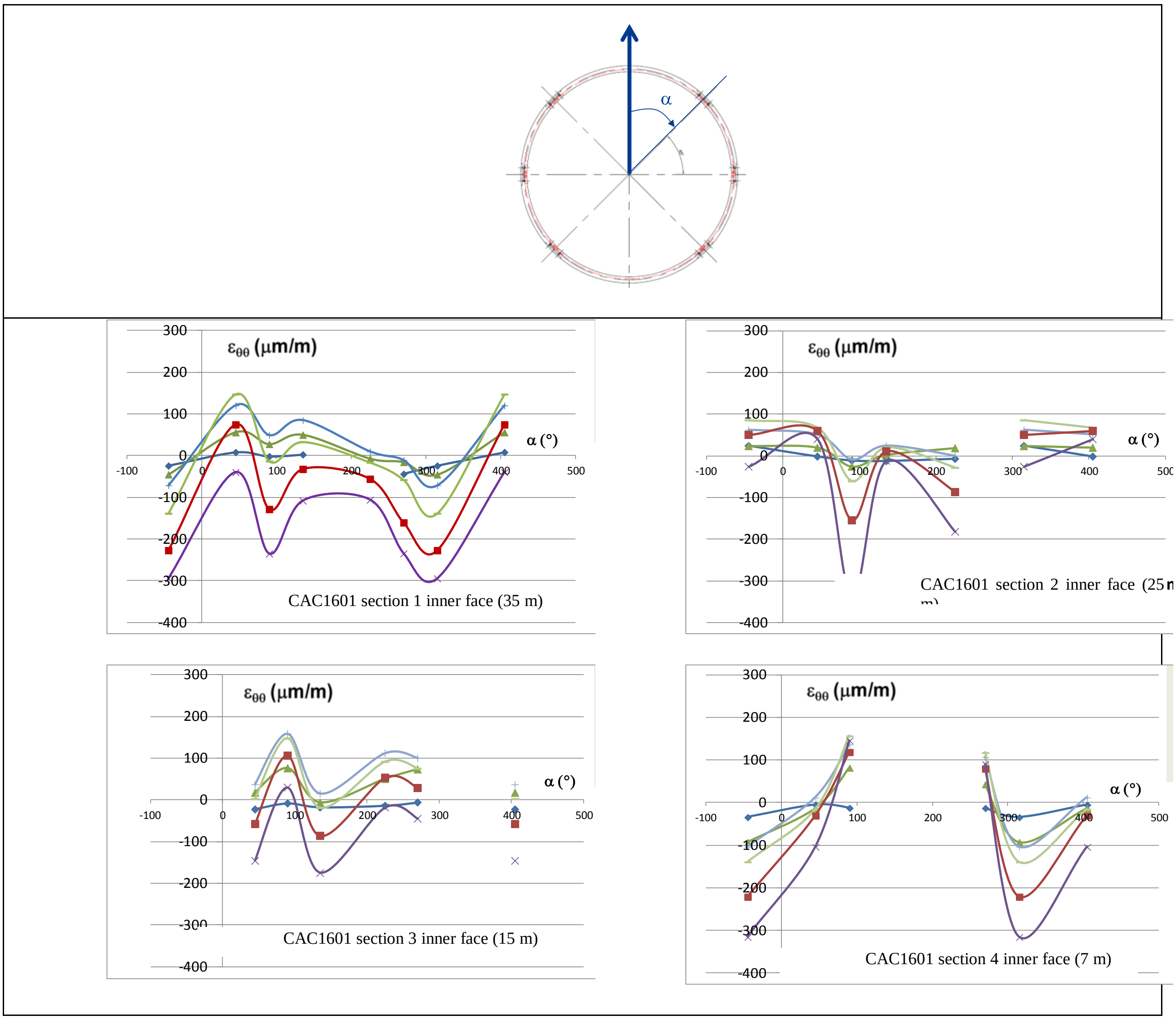

Figure 5-5-4: Evolution over time of the mechanical signatures of the casing (on the internal surface) and at different depths

Local strain measurements do not at this stage make it possible to trace them back to typical loading examples. A number of reasons can be put forward to explain this difficulty:

- the signals are incomplete due to the fact that some gauges are damaged;

- the level of strain is still low compared with that observed during small scale experiments;
- the mechanical loading applied to the casing is not yet stabilised.

Instrumentation by optical fibres sensors (OFS)

The measurement technique used for this instrumentation is the BOTDA (Brillouin-based Optical Time Domain Analysis) measurement system, which has the advantage of a good signal/noise ratio but the disadvantage of operating within an enclosed system.

External optical fibre instrumentation has been developed to detect possible falls of blocks of argillite through scaling after excavations. A length of reinforced optical fibre was attached to the interior of a u-profile, welded onto the longitudinal edge all along the casing. The installation was put in place at the same time as the excavation. Despite a specific protection, the welded part of the fibre did not withstand the stress generated during excavation work (mainly in the form of vibrations). This fibre is not currently recording any measurements.

Three of optical fibres were installed inside the casing after excavation (Figure 5-5-5):

- 1 fibre for Brillouin temperature measurement;
- 1 fibre for Brillouin deformation measurement; and
- 1 fibre for Raman temperature measurement, inserted in the same sheath.

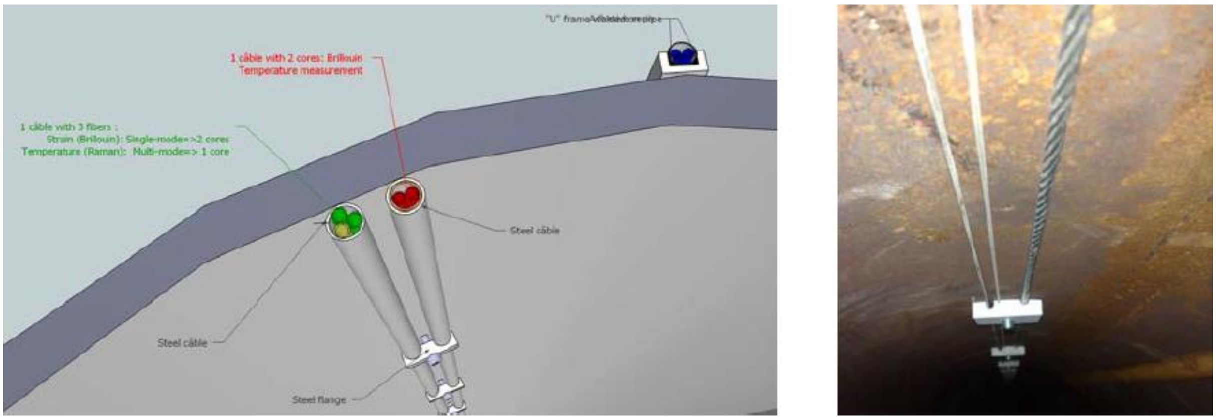

Figure 5-5-5: Instrumentation in OFS inside the casing – theoretical diagram (left) and photograph of the installed fibres (right: doubled fibre for temperature on the left; and deformation fibre on the right)

The cables containing the optical fibres were attached to the casing through flanges screwed on every 50 cm (Figure 5-5-5). The measurements acquisition started in February 2012.

Pore pressure in zones near the cell

The equipment installed consists of an aneroid pore pressure cell equipped with a vibrating wire sensor operating in sustain mode. The cell was placed in a measurement chamber filled with water and blocked off with quick-setting backfill of a very low permeability. The following figures show the system for enclosing the equipment put in place in borehole CAC1611.

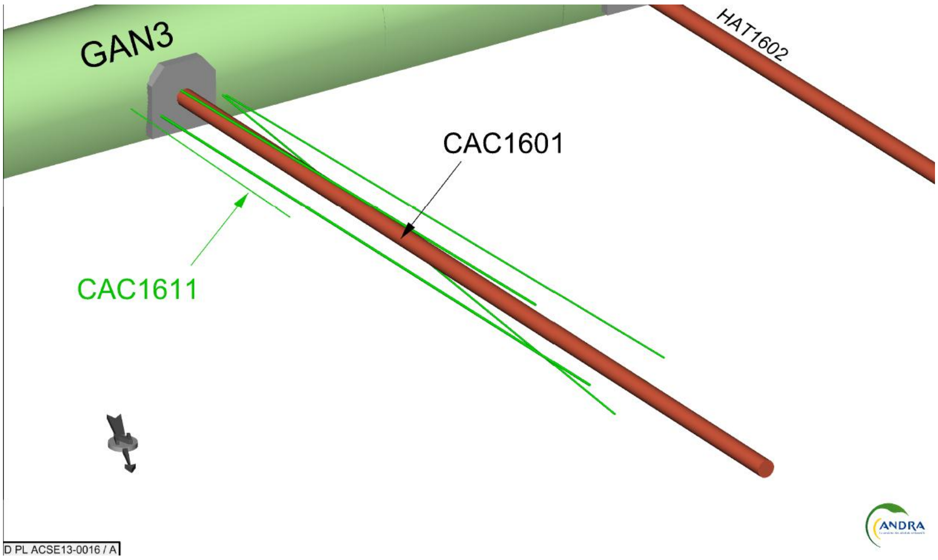

Figure 5-5-6: CAC1611 borehole surrounding the CAC1611 HL test cells

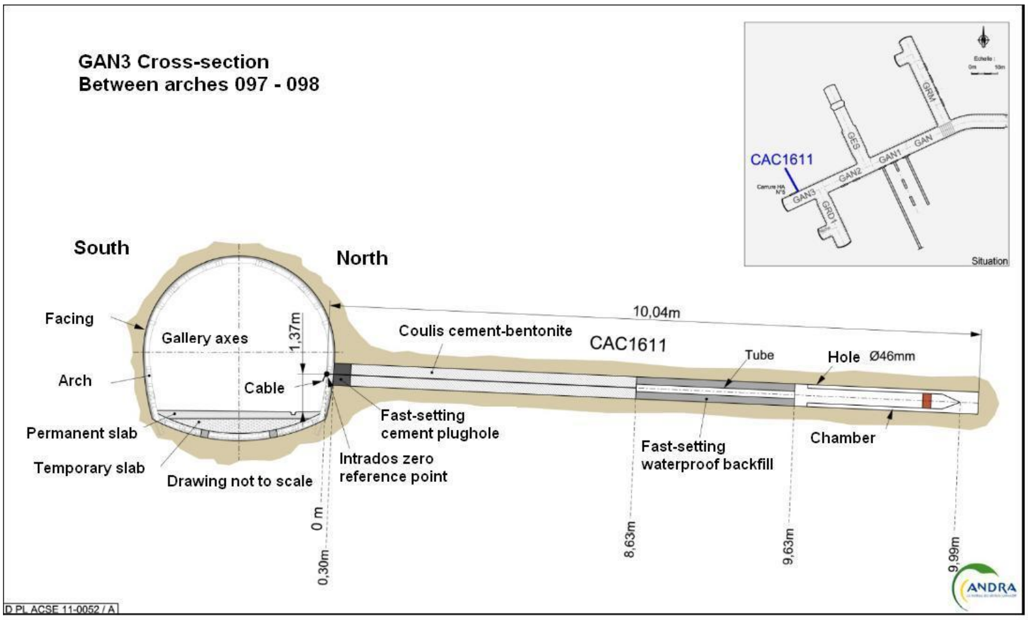

Figure 5-5-7: System for blocking off borehole CAC1611 equipped with a pore pressure sensor

The first results obtained (cf. figure below) show a slow and quasi-constant increase in pressure since the installation due to the very low permeability of the host rock and the kinetic of the water flow in the chamber.

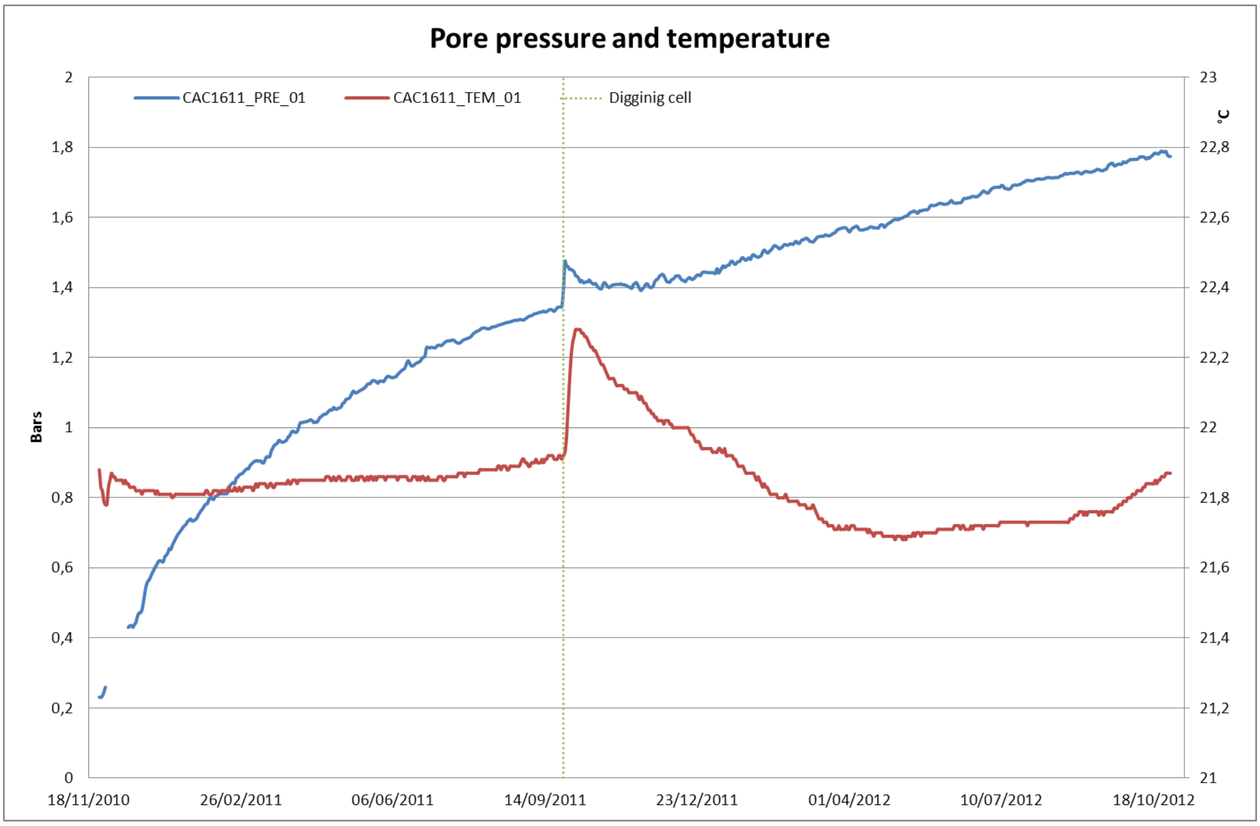

Figure 5-5-8: Evolution of pore pressure and temperature (in red) in borehole CAC1611.

An overpressure was observed on about 26 September 2011, corresponding to the passing of the cell excavation machinery near the cell. The rise in pressure returned to the same levels of increase after the dissipation of the overpressure resulting from the excavation.

5.5.6 Lessons learned

The experimental campaign demonstrated the feasibility of the complex instrumentation of casing with the aim of determining both its mechanical behaviour and the evolution of the hydromechanical conditions in the annular space. This instrumentation can only be installed after excavation. The feasibility of post-excavation optical fibre instrumentation was also demonstrated.

The evolution of the hydric conditions in the annular space showed that after approx. 300 days the arrival of water had not been observed, despite the watertightness of the casing (in the form of sealing between casing elements and bottom) and of the annular space at the front of the cell. On the other hand, measurement of convergence and local strains in the casing showed that it was subjected to mechanical load as soon as it had been installed in the ground. This load was localised in the horizontal direction, in accordance with what was observed during experiments on small-scale casing of similar orientation. These results show that the configuration of the casing of a High-Level Waste Cell undergoing stress exclusively from the pressure of water on its external surface is highly unlikely, especially since the casing to rock clearance initially foreseen in the 2009 design (25 mm in diameter) is less than that defined for the experiments (40 mm in diameter).

While the mechanical loading of the casing occurred very soon after its installation, it is nevertheless of a low intensity in relation to what was observed in small-scale casing over a comparable time-scale. This scale effect can be explained by the initial annular space, which, in proportion to its diameter, was larger in the case of cell, CAC1601.

5.5.7 Issues for further R&D

This monitoring demonstrator made it possible to validate the feasibility of the implementation of a pore pressure cell in such a geological environment, and with this type of equipment, the pore pressure cell test shows an increase in pressure that does not enable us to reach any conclusion concerning the suitability of this sensor for the future monitoring of Cigéo. Additional tests are required to obtain more realistic situations in terms of the measuring environment and in order to improve the arrangements in relation to 2 parallel aspects:

- To conceive a backfill for sealing off the borehole with satisfactory hydro-mechanical efficiency in the medium and long term;
- To test the cell with an effective "short-term" sealing system so as to validate the sensor's performance.

Distributed optical fibre sensors are also a clue technology for the monitoring of the planned French deep geological repository for long-lived high level and intermediate level wastes. Temperature and strain distributed sensing based on Raman, Rayleigh and Brillouin scatterings are being qualified, through diverse laboratory and field tests. Complementary to R&D being progressed to understand how to strengthen such sensors to radiations and other harsh conditions, a major requirement for distributed optical fibre sensing technology in harsh environments is the ability to work in single-end access configuration. This is especially important if an application involves embedded and/or other non-replaceable fibre installations. The distributed sensing using Rayleigh backscattering principle offers this specific feature. A new optoelectronic instrument based on this phenomenon will also be tested in order to assess the ability for external fibre measurement to detect falls of ground.

6 Synthesis

The MoDeRn technical work programme has included an extensive review of the current state-of-the-art of monitoring related to geological disposal. The programme covered the assessment of requirements for monitoring as well as embarking on five challenging research, development and demonstration programmes to apply state-of-the-art technology to experiments which simulated geological disposal in three European underground research facilities. The outcome of these work programmes (each of which can be viewed in more detail in the documents generated from the MoDeRn technical work programme and listed under references) is a better understanding of the capabilities and limitations of a number of monitoring techniques, particularly non-intrusive techniques.

There is a wide range of technologies available for repository monitoring. These include geophysical and remote sensing techniques that facilitate the acquisition of data on the general phenomena resulting from repository evolution. These phenomena include the surface manifestations of processes and events occurring within the repository, such as vertical displacement of the ground in response to first excavation (leading to subsidence) and then thermal expansion in response to the heat output from the waste (which leads to uplift). These techniques have limitations with respect to the achievable resolution and sensitivity and the information available from such techniques has limitations with respect to the safety performance of disposal.

There are however, several innovative technologies that could be applied for direct monitoring of the near field, and these technologies, which have been the focus of the MoDeRn studies, include non-intrusive monitoring where signals are transmitted and/or acquired remotely from the near-field, and in situ monitoring where measurements are taken in the near field and wireless data transmission systems are used to transfer the acquired data to receiver stations either within other (un-backfilled) parts of the repository or to the surface.

The technical experts workshop enabled valuable exchanges on monitoring with experts from a range of related industries, such as oil and gas, mining, nuclear and civil construction. Some of the techniques explored at that workshop, such as satellite interferometery may have useful applications in for example surveillance for safeguards or possibly for monitoring after closure (e.g. thermal impacts); likewise laser scanning may have applications in operational and routine safety monitoring.

The state-of-the-art review helps provide an understanding of the current technical capabilities of monitoring systems and helps to advise readers on the applicability and limitations of certain systems from specific monitoring applications. Although many techniques are identified as viable for monitoring geological disposal, the specific application in disposal cell monitoring can place more arduous requirements on the monitoring sensors, in particular the ability to withstand high temperatures, humidity and radiation fields. Additionally, the inaccessibility for repair or replacement and the very long times periods envisaged present significant challenges for *in situ* monitoring equipment. The requirement to minimise disturbance to the barriers also restricts the capability to apply more conventional monitoring relying on hard-wired connections between the sensors and receiver, housed external to the disposal cell.

The technical work conducted within the MoDeRn project has not resolved the capability for sustained monitoring of the very long timeframes for monitoring geological disposal, however, it has:

- progressed the understanding of what can be achieved;
- identified a number of alternative techniques which can be applied alongside each other to give a basis for cross-referencing performance; and
- clarified the potential and limitations for techniques identified.

The outcome from the MoDeRn work programme provides a basis for more focused research development & demonstration (RD&D) to address some of the limitations that have been identified, for example, the need for longer-lasting and durable power supply for remote sensors.

The key findings of the MoDeRn RT&D projects described in Chapter 5 are summarised below:

Seismic tomography

This work (see also MoDeRn 2013d and MoDeRn 2013n) was aimed at advancing the use of seismic monitoring technique as a means of non-intrusive monitoring employing full waveform inversion at the Grimsel Test Site (GTS), Switzerland. New algorithms for full waveform elastic inversion of seismic tomography data have been developed and practical methods for acquiring tomographic data have been developed through testing at Mont Terri and Grimsel. These developments enhance the ability to monitor a range of processes (e.g. saturation, and gas generation and migration) that affect the velocity structure of the near field. The key findings from this work were:

- Experimental design: Choosing a broad range of frequencies significantly increases the information content of seismic waveform inversion. Acquiring vectorial data, ideally employing directed sources and receivers, is important for performing elastic waveform inversions.
- The investigations indicated that acoustic approximation is not suitable for radioactive waste monitoring; elastic inversion is required instead.
- Low-velocity anomalies tend to be better resolved than high-velocity features.
- Anisotropic inversion was demonstrated as feasible but more research is necessary to address possible distortion of tomographic images.
- Sensor coupling is a critical issue, but a suitable algorithm was developed to determine coupling factors.

This technique would benefit from future development as follows:

- Further assessment/development of seismic sensors suitable for future monitoring experiments
- To improve the potential for elastic 3-D full waveform inversion by further development of efficient numerical modelling
- The investigation, in more detail, of the sensor coupling problem.

- A further assessment of the scope for applying this and other geophysical techniques to monitoring geological disposal, particularly considered in conjunction with wireless monitoring techniques.
- A role for such techniques in monitoring post-closure.

Overall, this technique can be used in conjunction with other monitoring techniques such as wireless sensor networks to monitor changes in the disposal cell in the early stages of evolution. In the initial stages it is important to ensure that the characteristics of the rock mass, such as anisotropy have been taken into account in correctly interpreting the information. This technique can be considered as non-intrusive and while the access area around a disposal cell remains open, the system can be maintained (e.g. replacement of receivers) without disturbing the disposal cell barriers. The technique has however some limitations in relation to: the relative proximity of the boreholes to the disposal cell; the quality of seismic information obtained; and access to the boreholes and seismic monitoring systems for individual cells would not be feasible as disposal areas are closed.

High frequency Wireless Sensor Networks

This research (see also MoDeRn 2013e and MoDeRn 2013n) evaluating the capacity for remote transmission from sensors embedded within a disposal cell using high frequency wireless (HFW) transmission, has demonstrated the viability of this technique at GTS, Switzerland, but also highlighted some of the challenges in sustaining such remote systems particularly with reference to sustaining power supply. The key findings from this work are:

- Testing of a range of UHF and VHF bands lead to the selection of 169MHz band to achieve the required balance between transmission distance and data transfer rates.
- The designed small HFW nodes, capable of incorporating up to four sensors, are capable of withstanding the harsh conditions within bentonite, rock and concrete.
- The developed wireless nodes included a lithium-thionyl-chloride battery with an expected lifetime of 20 to 25 years.
- Although in theory, energy harvesting would be feasible, utilising thermal gradient, analysis showed that the system would not be capable of providing the power in the required short burst without some form of power storage (capacitance). The use of super capacitors was evaluated but the energy leakage was similar to that required for the wireless node to function.

This technique would benefit from future development as follows:

- Exploring new methods for harvesting and storing energy to extend the potential operating life for remote sensors;
- Evaluation of performance in a radioactive environment;
- Improvement in reliability and miniaturisation of components;
- Improvements in transmission range including signal hopping

- Coupling with long range wireless data transmission to communicate directly with the surface.

Overall, this technique should benefit from further development, particularly on sustainable power sources and durability of sensors. The technique, unlike conventional wired systems, does provide a means of continuing to provide information after a disposal cell has been isolated without the risk of disturbing the constructed barriers. The potential for utilising this technique in conjunction with seismic tomography and a means of linking these systems to long range wireless data transmission systems could enable such information to be communicated remotely between underground and surface.

Fibre optic sensing

The use of fibre optic sensing (see also MoDeRn 2013f and MoDeRn 2013n) eliminates the need for calibration of inaccessible sensors. It does however rely upon the continued integrity of the optical fibre which in this case has been installed within protective tubing. The results so far show that the fibre optic sensors are capable of quantifying displacements with a resolution of 1 µm, permitting monitoring of very slow movements, typical of the evolution of long-term repository processes. This system will continue to be tested as the PRACLAY experiment continues beyond the duration of the MoDeRn Project and the results when the temperature is increased up to 100 °C will help provide information on the durability of fibre optic sensing in a high temperature environment, more typical of geological disposal. The Heater Test will commence once the required level of saturation and swelling of the bentonite seal has been achieved; this phase should assist in our understanding of how robust the technique of fibre optic sensing is to higher temperatures as well as providing information on the impact of such heating on the disposal cell construction and the surrounding geology.

The use of fibre optic sensing provides the potential for simpler and more robust sensing, which would be suited to geological disposal. Fibre optic sensing does however rely on the fibre breaching the barriers around the disposal cell but has significant advantages over conventional wired systems in reducing the number of breaches. Further consideration needs to be given to how fibre optic sensing can be used in conjunction with non-intrusive techniques discussed above.

Micro-seismic techniques

The seismic installation at HADES (see also MoDeRn 2013f and MoDeRn 2013n) is providing useful information on the changing properties of the Boom clay around the PRACLAY gallery. The seismic monitoring programme will continue to provide further information on these changes as the PRACLAY experiment continues. The development of the new seismic hammer has helped in the generation of high-energy, low-frequency shear waves.

The micro-seismic monitoring programme will also continue throughout the PRACLAY programme and will provide valuable learning on the use of this technique in monitoring changes. Continued experience in the recently developed seismic hammer will enhance the ability to progress effective S-wave monitoring and continue to provide information on changes to the EDZ as the heating experiment progresses.

Supercontainer monitoring

DIC and AE monitoring have been successfully used to detect crack initiation and growth during a half-scale test of the Belgian Supercontainer (see also MoDeRn 2013f and MoDeRn 2013n).

Corrosion sensors that can measure in situ corrosion rates have been developed and tested in surface facilities.

Long range low-frequency wireless data transmission

The experiments on long range wireless data transmission (MoDeRn, 2013g and MoDeRn, 2013n) tested and demonstrated the feasibility of wireless data transmission from an underground facility to the surface by low frequency magnetic fields. The key findings from this work are:

- Data transmission was demonstrated up to 100 bit/s even under unfavourable conditions as present at Mol, Belgium (high electrical conductivity of the host rock, limited space for transmission antenna and large local interference).

- The estimated of the energy need in order to transmit data from a generic Dutch disposal design in 500 m depth to the surface with a large antenna (r > 125 m) is <1mWs/bit.

- An approach was developed that enabled an estimate of the energy need for data transmission in other disposal situations/host rocks.

This technique would benefit from future development as follows:

- To establish the amount of data to be transmitted post-closure and over what duration.

- Development of a durable source of energy supply.

- Assessment of the durability of transmission system and development of durable components.

- Understand the significance of incidental data loss.

- Integration with other monitoring components.

Overall this technique provides the potential to allow communication of monitoring data between underground and surface. This technique provides some promise for post-closure monitoring, but requires more development to establish to address those areas discussed above.

Disposal cell monitoring systems

This programme (see also MoDeRn 2013h and MoDeRn 2013n) evaluated the capacity to design and install integrated monitoring systems and assess the capability to withstand construction and liner emplacement procedures within a mock-up high-level waste disposal cell at Bure in France. The key findings were:

- The feasibility of installing complex instrumentation within and on the casing of a disposal tunnel was demonstrated effectively;

- The instrumentation of the void space between the casing and the rock and strain gauges on the internal face of the casing allowed the deformation of the casing to be monitored effectively;

- The instrumentation of metallic liner by optical fibres:

    - inside the casing to measure the temperature and deformation profiles throughout the length of the casing;

    - on the metallic liner to detect possible fall of ground . A specific opto-electric instrument was required in order to effectively measure in this single-end access configuration.

Further development is currently being pursued to match specific repository requirements (durability, metrology, hardening to radiations, temperature, etc.):

- To continue the qualification of temperature and strain distributed optical fibre sensors, through diverse laboratory tests and metrological test benches;

- To make sensors more capable of withstanding radiation and other harsh conditions, by testing in irradiated facilities and adapting the fibre chemical compositions as appropriate,

- A new optoelectronic instrument based on Rayleigh backscattering principle was be tested to further assess the ability to work in single-end access configuration.

Concluding Remarks

Overall this work on disposal cell monitoring systems has demonstrated that, with planning and design, monitoring systems can be developed to operate effectively in harsh conditions. Developing and applying these techniques in these mock-up disposal cells has helped to understand some of the challenges and has permitted development to overcome these. As with all the techniques discussed above, trialling and development at an early stage will help improve the implementer’s understanding of the capabilities and limitations of the various techniques and to focus development in those areas where there is demonstrable value.

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 a better understanding of and confidence-building in the non-intrusive technique. It will help to ensure the provision of reliable, reproducible data when implemented to monitor a repository after waste emplacement and/or post-closure.

In taking monitoring development forward it is reasonable to propose that opportunities to develop and test monitoring system to enhance the state-of-the-art, should be a consideration in any programmes focused on disposal cell development and demonstration. This approach contributes to the “best value for money” while ensuring that geological disposal programmes continue to take opportunities to advance the development and robustness of monitoring techniques.

The use of disposal mock-ups supported by monitoring also provide the implementer with a means, through monitoring systems, of evaluating the disposal system design, thus providing, through learning, the possibility to further develop and optimise the design.

The work undertaken within the MoDeRn project has helped advance the state-of-the-art for a range of monitoring techniques, identifying what techniques are feasible, what are their limitations and has pointed to some areas for future development. There is clear value in evaluating a number of diverse techniques, which may be used for cross-reference and/or to replace another technique where monitoring information is no longer available.

Feedback from various stakeholders during the programme of consultation conducted under MoDeRn has pointed to a need to both consider post-closure monitoring and to understand what monitoring can capably be done after closure. This work has identified some potentially applicable techniques post-closure and there would be some value in exploring these and other potential applications. Of particular importance is the need to evaluate how the various techniques could be applied to practical monitoring situations – considering this against the sample case studies conducted under the MoDeRn Project (MoDeRn, 2013b) should help the implementer in this evaluation. The implementer should recognise the need to initiate a systematic design development for each monitoring, taking into account the specific national context, the geological environment and the types of waste being disposed of the ensure that the designed monitoring programme addresses the needs of that specific programme. The use of the MoDeRn Monitoring Workflow provides a structure to help provide better definition for the approach to monitoring; using this to help develop monitoring requirements, parameters of interest etc., which should help implementing bodies to focus on those monitoring techniques which are or could be significant to future programmes.

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