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[MoDeRn]

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Executive Summary

The EC Seventh Framework Programme Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) Project aims to develop the understanding of the role of monitoring in staged implementation of geological disposal to a level of description that is closer to the actual implementation of monitoring than previously achieved through collaborative international projects.

Work Package 2 of the MoDeRn Project is developing a description of the technical requirements on monitoring activities as well as an assessment of the state-of-the-art of relevant technologies that can be used to fulfil these requirements. A workshop on monitoring technologies (the Troyes Monitoring Technologies Workshop) was held as part of Work Package 2 at the Université de Technologie de Troyes (UTT), France on 7-8 June 2010. This document provides a record of the workshop.

The Troyes Monitoring Technologies Workshop brought together 55 experts from a range of organisations, including industry, radioactive waste management organisations and research institutes. The workshop provided an opportunity for communication between these different groups.

The main aim of the workshop was to bring together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art techniques to monitoring. The specific objectives of the workshop 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 with a monitoring component.

The workshop was structured to support these objectives, with three main elements:

- Fourteen talks were presented in five technical sessions:
  - 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.

  Each technical session was followed by a discussion session.
- Three poster sessions were held in which 21 posters were presented. The poster sessions had a wider scope than the oral sessions, and provided opportunities for discussion and technical exchanges.

- A round-table plenary discussion reviewed the session topics, identified synergies in approach and opportunities for knowledge transfer and/or collaboration, and identified where there may be benefits in future development of monitoring technologies.

The discussion of the state-of-the-art in these monitoring technologies provided a useful platform for the MoDeRn project partners to use during the remainder of the project. Research and development (R&D) projects with a monitoring component were identified and discussed, including:

- ESDRED: Engineering Studies and Demonstration of Repository Designs.
- FIDES: Optical Fibres for New Challenges Facing the Information Society.
- I-SSB: The Integrated Safe and Smart Built Concept.
- LIMES: Land and Sea Monitoring for European Security.
- OFSESA: Novel and Reliable Optical Fibre Sensor Systems for Future Security and Safety Applications.
- OMNIBUS: Development of the Tools and Interpretation Techniques for Ultrasonic Surveys to Monitor the Rock Barrier around Radioactive Waste Packages in Geological Repositories.
- POLYTECT: Polyfunctional Technical Textiles against Natural Hazards.
- RAINOW: Researching the Applications of Open Innovative Wireless Technologies.
- Sustainable Bridges: Assessment for Future Traffic Demands and Longer Lives.
- TIMODAZ: Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks.

Conclusions regarding the state-of-the-art for the various types of monitoring presented at the Troyes Monitoring Technologies Workshop are as follows:

- Wireless sensor networks (WSNs): Battery power limits the operation of WSNs to 1-2 years. Data processing techniques can reduce the quantity of data requiring transmission by 99%, which may lead to increasing effective operating time to 10 years.
- Wireless through-the-earth transmission: Current developments suggest the feasibility of direct transmission of a limited amount of data from the repository to the surface, over a period of one or several decades.
- Fibre optic sensors: Fibre optic sensors are available for the measurement of temperature and strain, with some capability for measuring these parameters on a distributed basis. Glass optical fibres can measure strains of 1%, whereas polymer optical fibres can potentially measure strains up to 40% and have been demonstrated to measure strains up to 20%.

- Seismic interferometry: Developments in coda wave analysis allow for the monitoring of temporal changes in the average properties of a medium (e.g. pressure as a result of thermal expansion) of ~0.1% – 0.01%.

- Time-lapse 3D seismics: Estimates of the volume of CO_2 imaged on 3D seismic surveys of the Sleipner Field in the North Sea accounts for 85% of the injected CO_2.

- Acoustic emissions and microseismicity (AE/MS): AE/MS events have been monitored in response to changes in pressure (of 4 MPa) and changes in temperature (of 6°C) in underground research laboratories.

- Borehole multiple completion methods for fluid pressure measurement have recently been extended to depths of ~2,400 m and instrumentation has been upgraded to allow measurement of pressures up to 5000 psi.

- Strain monitoring using extensometers and tell-tales: Tell-tales can monitor millimetre-scale displacements in tunnels.

- Stress monitoring: Installation of multiple point systems prior to tunnel excavation can detect the impact of excavation on the *in situ* stress up to 100 m from the tunnel. Monitoring of coupled stress and deformation in a range of underground settings has illustrated that stress can be used as a good indicator that deformation might happen; a sensor has been developed that auto-corrects its "0" point.

- Laser scanning: Laser scanning has been used to develop 3D models of underground excavations that can resolve features as small as 5 mm in diameter, with 3-5 cm spatial accuracy, when the laser scanning devices are placed up to 1 km from the target.

- Satellite imagery: Optical imaging technology is readily available with a 50 cm resolution.

- Radar interferometry: Corner Reflector Interferometric Synthetic-aperture Radar (CRInSAR) provides millimetre-scale monitoring of changes in ground elevation.

Developments in the state-of-the-art in monitoring technologies will be undertaken in the MoDeRn Project. These will include:

- Improving the range of low-frequency based wireless through-the-earth transmission.

- Adapting ZigBee and similar wireless sensor nodes and transmission network to the repository environment.

- Development of remote, wireless energy transfer to recharge batteries.

- Improving the resolution of geophysical monitoring techniques, in particular through the development of improved waveform analysis tools.

- Developing Brillouin scattering fibre optic sensors for use in a heated gallery.

- Developing short and long-term monitoring of cement-based grout, combining time-domain reflectometry (TDR), deformation gauges and ultrasonic characterisation.

In addition, demonstration and development of wireless and non-intrusive monitoring techniques will be undertaken. These activities will be applied to monitor mock-ups that equate to repository conditions and allow typical parameters from these mock-ups to be monitored. The mock-ups will be developed in underground research laboratories (URLs): the Grimsel Test Site, the HADES URL and the Bure URL.

Repository monitoring programmes must be based on the specific context within which they are undertaken, and it was recommended that value would be provided to waste management organisations if generic approaches to monitoring were developed as part of the MoDeRn Project.

List of Acronyms

AE: Acoustic Emission

AECL: Atomic Energy Canada Limited

AEM: Acoustic Energy Meters

Andra: Agence Nationale pour la Gestion des Déchets Radioactifs, France

BAM: Federal Institute for Materials Research and Testing, Berlin

CAD: Computer-aided Design

CCS: Carbon Capture and Sequestration

CPU: Central Processing Unit

CRInSAR: Corner Reflector InSAR

CSIRO: Commonwealth Scientific and Industrial Research Organisation, Australia

CTU: Czech Technical University

DifSAR: Differential InSAR

DoW: Description of Work

EBS: Engineered Barrier System

EDZ: Excavation Damaged Zone

EC: European Commission

EIS: Electrochemical Impedance Spectroscopy

EMPA: Swiss Federal Laboratories for Materials Testing and Research

ESDRED: Engineering Studies and Demonstration of Repository Designs (EC Project)

ETN: European Thematic Network

ETS: Emission Trading Scheme

EU: European Union

EURIDICE: European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment

FIDES: Optical Fibres for New Challenges Facing the Information Society

GCP: Ground Control Point

GSL: Galson Sciences Ltd. UK

GTS: Grimsel Test Site

GUM: Guide for the Expression of Uncertainty in Measurement

HAW: Higher-activity radioactive waste

HLW: High-level Waste

HRL: Hard Rock Laboratory

IAEA: International Atomic Energy Agency

ILW: Intermediate-level Waste

InSAR: Interferometric Synthetic-aperture Radar

ISHMII: International Society for Structural Health Monitoring of Intelligent Infrastructure

LED: Light-emitting Diode

LIBS: Laser Induced Breakdown Spectroscopy

LIMES: Land and Sea Monitoring for European Security

LNE: Laboratoire National de métrologie et d'Essais

LNIO: Laboratoire de Nanotechnologie et d'Instrumentation Optique

MoDeRn: Monitoring Developments for Safe Repository Operation and Staged Closure

MS: Microseismicity

NDA: Nuclear Decommissioning Authority

NPT: Non-proliferation Treaty

OFSESA: Novel and Reliable Optical Fibre Sensor Systems for Future Security and Safety Applications

OMNIBUS: Development of the Tools and Interpretation Techniques for Ultrasonic Surveys to Monitor the Rock Barrier around Radioactive Waste Packages in Geological Repositories

OP: Oral Presentation

OTDR: Opticus Supply Fibre Optic

PC: Personal Computer

PFC: Particle Flow Code

POLYTECT: Polyfunctional Technical Textiles Against Natural Hazards

POF: Polymer Optical Fibre

PP: Poster Presentation

PRACLAY: Preliminary demonstration test for clay disposal of highly radioactive waste

PSI: Persistent Scatterer Interferometry

R&D: Research and Development

RAINOW: Researching the Applications of Open Innovative Wireless Technologies

RAWRA: Radioactive Waste Repository Authority, Czech Republic

RF: Radio Frequency

RTD: Research and Technological Development

RWMC: Radioactive Waste Management Funding and Research Center, Japan

SAR: Synthetic-aperture Radar

SHM: Structural Health Monitoring

SOFO: Monitoring of Structures by Optical Fibres

SWIFTS: Stationary Wave Integrated Fourier Transform Spectrometer

TDR: Time-domain Reflectometry

TECDOC: Technical Document

TEM: Testing and Evaluation of Monitoring Systems

THMC: Thermal, Hydro, Mechanical and Chemical

TIMODAZ: Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks

TSX: Tunnel Sealing Experiment

UEF: Underground Educational Facility

UTT: Université de Technologie de Troyes

URL: Underground Research Laboratory

VIM: International Vocabulary of Metrology

VLF: Very-low Frequency

VSP: Vertical Seismic Profile

WIPP: Waste Isolation Pilot Plant, US

WP: Work Package

WSN: Wireless Sensor Networks

1. Introduction

1.1 Background to the MoDeRn Project

The successful implementation of a repository programme relies on both the technical aspects of a sound safety strategy, and scientific and engineering excellence, as well as on social aspects such as public acceptance. Monitoring has the potential to contribute to both of these aspects and thus has an important role to play as national radioactive waste disposal programmes move forward towards a successful conclusion, i.e. safe and accepted implementation of geological disposal.

The role of monitoring through the staged implementation of geological disposal has been considered on an international basis through production of an International Atomic Energy Agency (IAEA) Technical Document (TECDOC) on monitoring of geological repositories (the IAEA Monitoring TECDOC) (IAEA, 2001) and by the European Commission (EC) within a Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste (the Monitoring ETN) (EC, 2004). These two documents have described how monitoring can support the implementation of geological disposal in a broad sense. The EC Seventh Framework Programme "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn) Project aims to further develop the understanding of the role of monitoring in staged implementation of geological disposal to a level of description that is closer to the actual implementation of monitoring.

Work in the MoDeRn Project is undertaken in a comprehensive and coherent programme of research structured into six interrelated work packages:

- **Work Package 1: Monitoring Objectives and Strategies:** Work Package 1 will provide a clear description of monitoring objectives and strategies that (i) appear suitable in a given physical and societal context, (ii) may be implemented during several or all phases of the radioactive waste disposal process, (iii) appear realistic in light of available monitoring technology, (iv) take into account feedback from both expert and lay stakeholder interaction, and (v) provide information to support decision-making processes, while developing the licensing basis.

- **Work Package 2: State-of-the-art and RTD of Relevant Monitoring Technologies:** The second work package will result in a description of the technical requirements on monitoring activities as well as an assessment of the state-of-the-art of relevant technology responding to these requirements; it includes a technical workshop involving other monitoring Research and Technological Development (RTD) projects (the subject of this document), leading to the identification of RTD techniques that enhance the ability to monitor a repository.

- **Work Package 3: *In situ* Demonstration of Innovative Monitoring Technologies:** The third work package will develop *in situ* demonstration of innovative monitoring techniques and provide a description of innovative monitoring approaches specifically responding to some of the design requirements of a repository.

- **Work Package 4: Case Study of Monitoring at All Stages of the Disposal System:** The fourth work package will be dedicated to a series of case studies illustrating the process of mapping objectives and strategies onto the processes and parameters that need to be monitored in a given context, the possible design of corresponding monitoring systems, possible approaches to prevent and detect measurement errors, and the handling of "unexpected" repository evolutions.

- **Work Package 5: Dissemination of Results:** The fifth work package will provide a platform for communicating the results of the MoDeRn Project. Two international meetings will be held, an international workshop with safety, regulatory and advisory authorities to communicate current state-of-the-art monitoring approaches and to engage expert stakeholders in the further development of repository monitoring objectives and strategies, and an international conference on repository monitoring. The work package also includes production and maintenance of a project web site.

- **Work Package 6: Reference Framework:** The final work package will consolidate results from the previous work packages and provide a shared international view on how monitoring may be conducted at the various phases of the disposal process. Early work in the MoDeRn Project has contributed to the reference framework by drafting a generic structured approach to monitoring - the MoDeRn Monitoring Workflow, which provides a methodology for developing and implementing a monitoring programme under specific national boundary conditions (Figure 1.1). The relationship of the MoDeRn Monitoring Workflow to work being undertaken in the project is illustrated in Figure 1.2.

As part of Work Package 2, a workshop on monitoring technologies (the Troyes Monitoring Technologies Workshop) was held at the Université de Technologie de Troyes (UTT), France on 7-8 June 2010. Fifty-five participants attended the meeting (Figure 1.3), with representatives from a wide range of different industries and research institutes. Appendix A provides a list of attendees and their affiliations. The agenda for the workshop is provided in Appendix B.

This document provides a record of the workshop. It has been prepared by Galson Sciences Ltd (GSL) and has been reviewed by workshop participants.

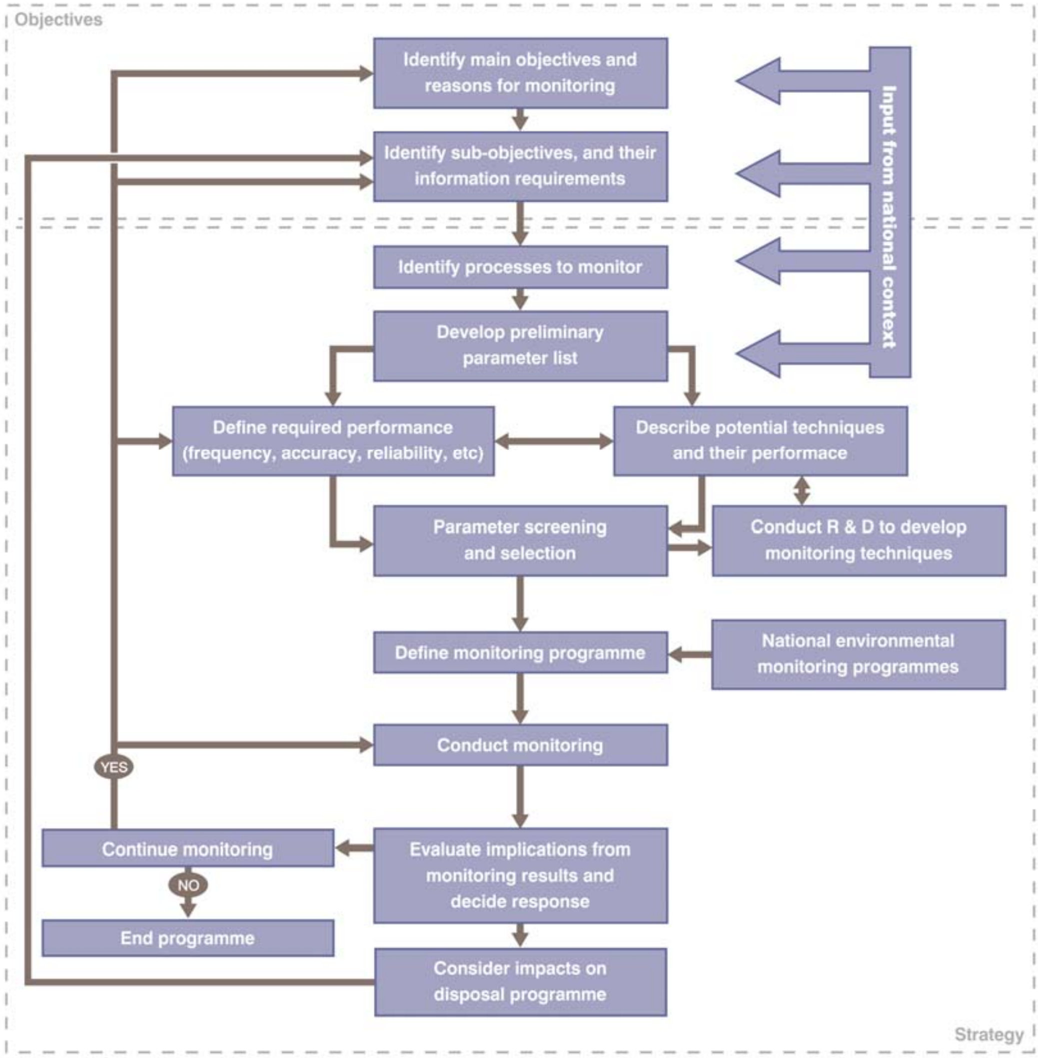

Figure 1.1: The Preliminary MoDeRn Monitoring Workflow.

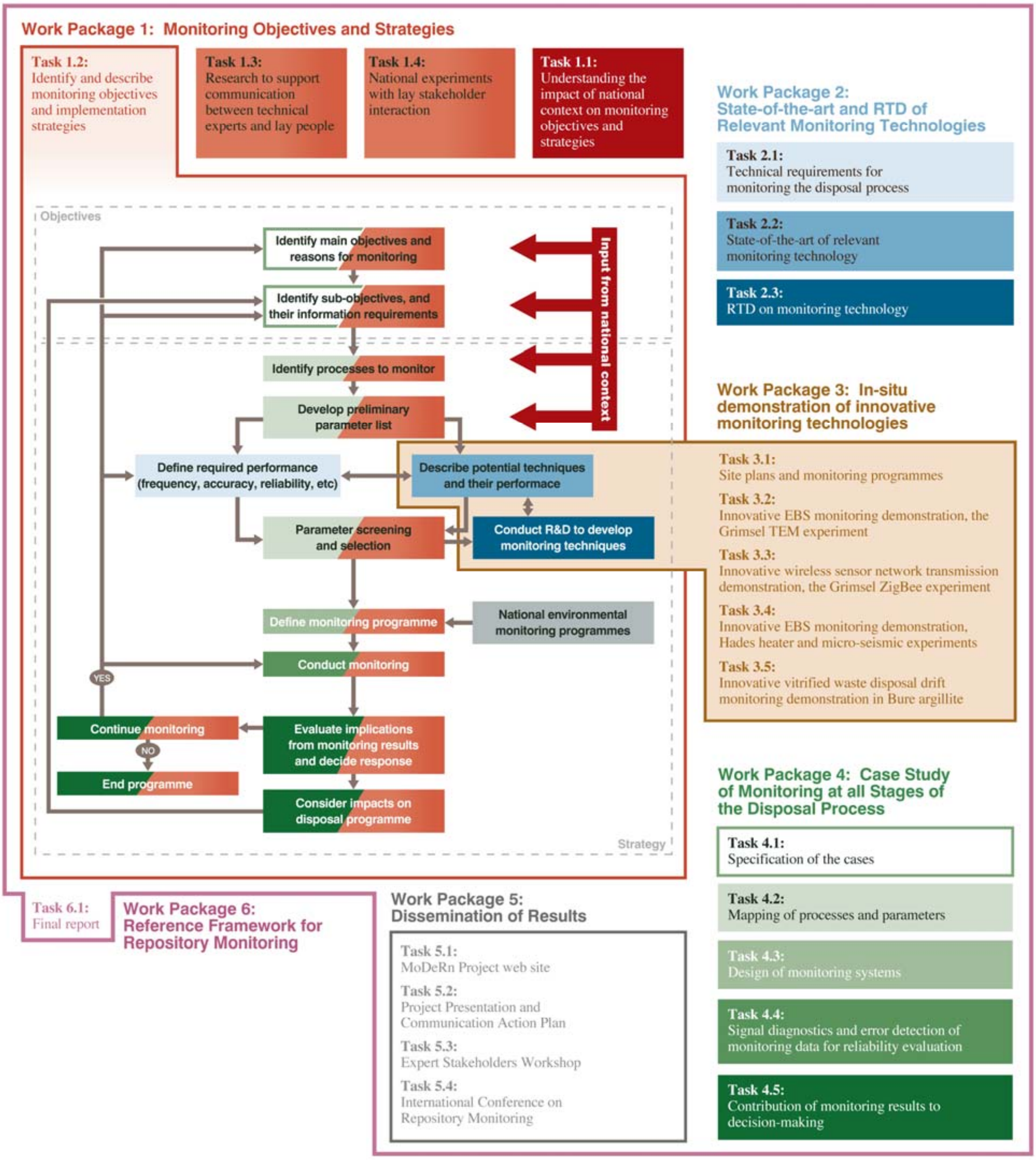

Figure 1.2: Relationship of the Preliminary MoDeRn Monitoring Workflow to MoDeRn Project work package tasks.

Figure 1.3: Group photograph of the participants at the Troyes Monitoring Technologies Workshop.

1.2 Report Objectives

The objectives of this report are:

- To provide a record of the Troyes Monitoring Technologies Workshop.
- To summarise the material presented at the workshop.
- To summarise workshop discussions on monitoring applications and technologies used in other industries, and to discuss their potential for application to radioactive waste disposal, supported by information provided in workshop presentations and posters.
- To capture the opportunities for further research, development, demonstration and collaboration between monitoring experts.

The discussions at the workshop covered monitoring technologies relevant to radioactive waste repositories, focusing on those that provide particular challenges for application in the context of radioactive waste disposal. The report is not a comprehensive description of the state-of-the-art (which will be the subject of a future MoDeRn Project Report). Omissions are noted where identified.

1.3 Workshop Background

The main aim of the workshop was to bring together monitoring specialists from a range of disciplines to present and discuss their work and experience in applying state-of-the-art techniques to monitoring. The specific objectives of the workshop were to:

- Review recent developments in monitoring technologies.
- Stimulate mutually beneficial exchanges 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 with a monitoring component (see Appendix C for a list of EC projects with a monitoring component).

The workshop was structured to support these objectives, with three main elements:

- Fourteen talks were presented in five technical sessions:
  - 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.

  Each technical session was followed by a discussion session. Abstracts for the oral presentations (OPs) are provided in Appendix D.
- Three poster sessions were held in which 21 posters were presented. The poster sessions had a wider scope than the oral sessions, and provided opportunities for discussion and technical exchanges. Appendix E provides the abstracts for the poster presentations (PPs).
- A round-table plenary discussion reviewed the session topics, identified synergies in approach and opportunities for knowledge transfer and/or collaboration, and identified where there may be benefits in future development of monitoring technologies.

The workshop presentations focused on monitoring technologies and the way they were currently being applied. This allowed a broad view of the state-of-the-art in several monitoring technologies to be established.

1.4 Report Structure

The report is structured as follows:

- Section 1 describes the background to the Troyes Monitoring Technologies Workshop, the objectives of the workshop, and the objectives and structure of the report.

- Section 2 provides a high-level summary of repository monitoring.

- Section 3 describes the presentations and discussions during the workshop relating to applications of monitoring, including engineering, radioactive waste storage, mine safety, and carbon capture and sequestration.

- Section 4 describes the presentations and discussions held at the workshop relating to technologies, including wireless transmission, fibre-optic sensor networks, geophysics, hydrogeological and hydrogeochemical monitoring, and air-based and satellite-based methods.

- Section 5 summarises discussion at the workshop on monitoring technologies, identifies technological developments that could be undertaken in the MoDeRn Project, in research and development (R&D) undertaken as part of other radioactive waste disposal programmes, and in R&D undertaken in other industries. The discussion also provides an overall evaluation of the workshop and collaboration opportunities identified at the workshop.

- Section 6 provides conclusions drawn from the discussion presented in this report.

2. Overview of Repository Monitoring

This section provides a high-level overview of monitoring in the context of the disposal of radioactive waste in geological repositories. It is included to provide context to the discussions in subsequent sections of this report. Further information on monitoring of geological repositories can be found in the IAEA TECDOC (IAEA, 2001) and the report of the Monitoring ETN (EC, 2004).

Geological disposal is the internationally accepted solution for the management of long-lived radioactive waste, in order to protect man and the environment. Safety of geological disposal is demonstrated by a disposal safety case, and, therefore, we describe the role of a safety case in Section 2.1. Section 2.2 provides a summary of the role of monitoring in geological disposal in general, and in particular how it may contribute to confirm the basis for repository safety. Section 2.3 provides some examples of monitoring objectives.

At the Troyes Monitoring Technologies Workshop, an introduction to geological disposal of radioactive waste was provided by Brendan Breen (Nuclear Decommissioning Authority (NDA)). Stefan Mayer (Andra) introduced the scope of the MoDeRn Project (supported by a poster by Matt White of GSL - see abstract PP.1 in Appendix E) and outlined key considerations for repository monitoring. The discussion in this section is based on these presentations.

2.1 Geological Disposal and the Safety Case

Worldwide, there are forty-seven countries with significant volumes of radioactive waste and materials, which have arisen from nuclear power generation and from military, medical and research activities. Many of these wastes will remain hazardous over long periods. The fundamental objective of disposing of radioactive wastes is to protect people and the environment from harmful effects of ionising radiation (IAEA, 2006a). The geological disposal system (the disposal facility and the geological environment in which it is sited) is developed in a series of steps in which the scientific understanding of the disposal system and of the design of the geological disposal facility is progressively advanced (IAEA, 2006b). The basis for this understanding of the disposal system and the key arguments for its safety, and an acknowledgement of the existing unresolved uncertainties, of their safety significance and approaches for their management, are incorporated into a safety case (IAEA, 2006b).

Most countries with significant volumes of radioactive waste and materials have programmes to address radioactive waste management through geological disposal in repositories. These programmes are at different stages of development, from preliminary planning to operating facilities for geological disposal, and consider repositories hosted in a range of geological environments, including different host rocks.

The role of the safety case may include (EC, 2010):

- Integrating relevant scientific, technical and other information in a structured, traceable and transparent way and, thereby, **developing and demonstrating an understanding of the feasibility and potential behaviour and performance of the disposal system**.

- Identifying uncertainties in the behaviour and performance of the disposal system, describing the possible significance of the uncertainties, and **identifying approaches for the management, or further treatment, of significant uncertainties**.

- Demonstrating long-term safety and **providing reasonable assurance that the disposal facility will perform** in a manner that adequately protects human health and the environment.

- **Facilitating communication amongst stakeholders** on issues relating to the disposal facility and explaining why the audience should have confidence in the acceptability of the disposal facility.

- Aiding **decision-making** on the authorisation / licensing of radioactive waste disposal and related issues.

Geological disposal aims to isolate and contain waste through appropriate design and operation of the facility, through siting in a suitable geological environment, and by using an appropriate engineered barrier system (EBS). The EBS consists of man-made components of the multi-barrier system including, as appropriate, the waste form, the waste containers, the buffer, the backfill, the repository seals and other engineered features. The geological barrier consists of the rock and groundwater system that isolates the waste from the biosphere, contains and retards radionuclides and protects the EBS. To be effective, the disposal system design, including the choice of engineered barriers, must be tailored to the specific geological environment in which it is to function, and monitoring has a role to play in understanding the performance of both the EBS and the surrounding geological environment.

2.2 Role of Monitoring in Geological Disposal

Monitoring during the implementation of geological disposal can be used to support the scientific and technical programme, and can be used to build societal acceptability. Monitoring has been defined in the Monitoring ETN (EC, 2004) as:

> *"Continuous or periodic observations and measurements of engineering, environmental, radiological or other parameters and indicators/characteristics, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment, and to help in making decisions on the implementation of successive phases of the disposal concept."*

The IAEA has identified the key requirements concerning monitoring programmes related to geological repositories (IAEA, 2006b):

- *"A programme of monitoring shall be defined and carried out prior to and during the construction and operation of a geological disposal facility. This programme shall be designed to collect and update the information needed to confirm the conditions necessary for the safety of workers and members of the public and the protection of the environment during the operation of the facility, and to confirm the absence of any conditions that could reduce the post-closure safety of the facility.*

- *"Monitoring is carried out during each step of the development and operation of the geological disposal facility. The purposes of the monitoring programme include providing baseline information for subsequent assessments, assurance of operational safety and operability of the facility, and confirmation that conditions are consistent with post-closure safety. Monitoring programmes are designed and implemented so as not to reduce the overall level of post-closure safety of the facility.*

- *"… Plans for monitoring with the aim of providing assurance of post-closure safety are drawn up before construction of the geological disposal facility to indicate possible monitoring strategies, but remain flexible and, if necessary, will be revised and updated during the development and operation of the facility."*

Specific roles of monitoring in support of the scientific and technical programme include:

- To build confidence in the long-term safety case, including demonstration that the facility is evolving as expected.
- To build confidence in construction and operation.
- To demonstrate appropriate environmental performance.
- To maintain nuclear safeguards.
- To support stakeholder acceptability.
- To provide information for making management decisions (e.g. retrievability).

The work undertaken as part of the MoDeRn Project is focusing mainly on monitoring in support of long-term safety. There are specific challenges to developing such monitoring programmes, for example:

- Can *in situ* monitoring systems provide several decades of maintenance-free, reliable monitoring without intervention?
- Can information be collected on slow processes when the timescale for monitoring is limited, compared with the expected evolution of the disposal system?
- Can monitoring technologies withstand environmental conditions within the repository, which may include high mechanical and/or hydraulic pressure, chemically corrosive groundwater, elevated temperatures, and irradiation levels of several Gy/hr near waste packages?
- Can monitoring systems be successfully implemented without undermining the integrity of engineered and natural barriers (for example, through the use of non-intrusive techniques and/or wireless data transmission)?

Different approaches to monitoring are appropriate during planning, construction and operation, and after operation. Prior to construction and operation, substantial knowledge and monitoring experience will be available from:

- Decades of science and technology research programmes.
- Site characterisation and monitoring of site baseline conditions.
- Experiments and demonstrations in surface laboratories and underground research laboratories (URLs).

During construction and operation, ongoing monitoring will provide data that can be used to support the understanding of how the natural and engineered systems are responding to the development of the repository. This will provide information on operational safety (e.g. the potential for rock falls), the long-term safety case (e.g. understanding the transient response of the hydrogeological regime to excavation of the repository), and environmental impact (understanding the impact of the repository on the surface). Monitoring data will support optimisation of the disposal facility design. The use of monitoring data in developing the understanding of the site will also play an important role in responding to any authorisation conditions placed on operation of the facility by the regulators and in building confidence of stakeholders.

Once the repository is operating, monitoring will play an important role in ensuring safeguards and in demonstrating retrievability of waste (where this is a requirement of the national programme).

Monitoring following operation of a repository will be dependent on decisions made by future generations. Post-emplacement monitoring could extend into the post-closure period (the period of institutional control). Depending on the national context, monitoring during the early stages of repository implementation will need to reflect this possibility (i.e. gather baseline information against which post-closure monitoring data can be compared).

2.3 Examples of Monitoring Objectives, Processes and Parameters

The objectives of a monitoring programme are dependent on the national context under which the programme is developed. The national context includes relevant regulations, the nature and quantities of the waste to be disposed of, the repository design, the geological environment and stakeholder expectations.

An example of processes in different parts of a repository that a repository monitoring programme might cover is provided below, based on a generic conceptual design for the engineered barrier system of a high-level waste (HLW) repository illustrated in Figure 2.1:

- Waste disposal packages:
    - Containment of waste.
    - Mechanical and chemical stability of waste packages.
- Other engineered components (buffers, backfills, seals and structural components):
    - Containment of waste in repository – resistance to groundwater flow and transport through the repository.
    - The consistency of thermal, hydro, mechanical and chemical (THMC) conditions with the assumptions made in the safety case.
- Natural environment (near-field geological environment):
    - Minimise perturbation of host rock – preserve favourable groundwater flow and transport conditions.
    - Evolution of THMC properties relevant to the safety case.

- Natural environment (far-field geological environment):
  - Rock mechanics, hydrogeological and hydrogeochemical response to repository development and evolution.

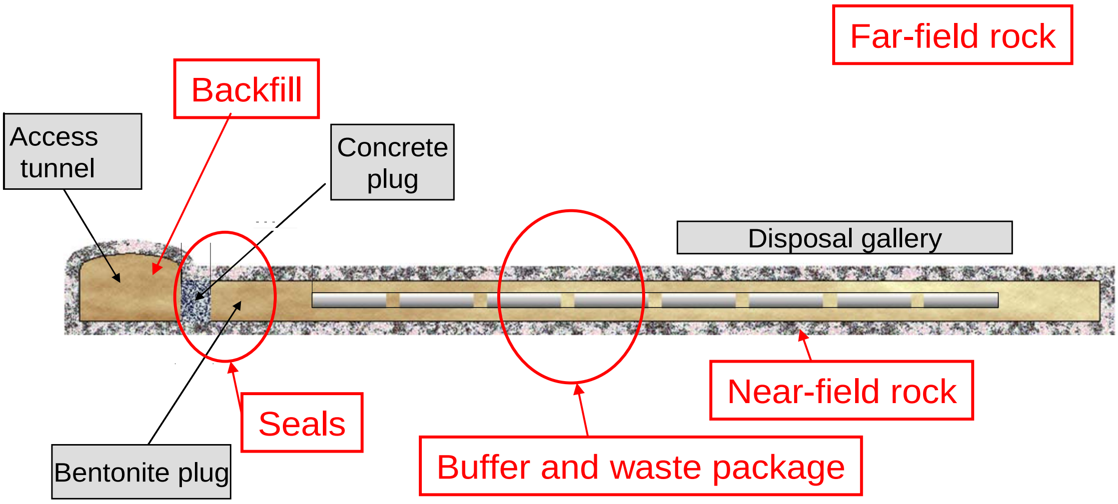

Figure 2.1: Illustration of the components and layout of a generic conceptual design for the engineered barrier system of a HLW repository.

Several presentations at the Troyes Monitoring Technologies Workshop described elements of monitoring programmes and of monitoring technology R&D specifically conducted to support radioactive waste disposal. These included:

- PP.6: Jiro Eto (RWMC) described a database of monitoring technologies (the Technical Menu) developed as part of the Japanese radioactive waste disposal programme.
- PP.7: Stéphane Buschaert (Andra) provided a summary of R&D on monitoring technologies undertaken by Andra as part of its research programme on repository monitoring.
- PP.8: Ronan Morice, (LNE) discussed the contribution of metrology to the monitoring of geological repositories.
- PP.9: Roman Špánek (Technical University of Liberec) described the system of monitoring used in the Bedřichov water tunnel in the Czech Republic.
- PP.18: Svoboda Pacovsky (CTU) described *in situ* monitoring of the Josef underground facility in the Czech Republic.

3. Monitoring Applications

This section reviews aspects of the Troyes Monitoring Technologies Workshop related to monitoring applications. The discussion focuses on integrated monitoring approaches other than radioactive waste disposal that were discussed at the Troyes Monitoring Technologies Workshop:

- Engineering (Section 3.1).
- Radioactive Waste Storage (Section 3.2).
- Mining (Section 3.3).
- Carbon Capture and Sequestration (Section 3.4).

Representatives from the oil and gas industry were invited to the meeting but were unable to attend.

For each application:

- A high-level summary of the role of monitoring is provided.
- Presentations related to the application are listed, and a reference given to the abstract number (OP refers to oral presentations, which can be found in Appendix D, and PP refers to poster presentations, which can be found in Appendix E).
- The discussions at the workshop are summarised.

3.1 Engineering: Structural Health Monitoring

In engineering, structural health monitoring (SHM) is the process of implementing a damage detection and characterisation strategy for engineering structures. Here, damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. SHM is commonly used in the monitoring of bridges and in the aviation industry, where it is used to detect the onset of damage.

SHM has potential application in the monitoring of engineered structures in repositories. In particular, the technologies and approaches adopted for SHM could be adapted for radioactive waste disposal projects, e.g. to monitor the integrity of disposal cell seals. Example applications of SHM may provide lessons in successful and unsuccessful strategies for application in repositories, e.g. examples of the quantity of data required for detection of failure of engineering structures.

Presentations on SHM at the Troyes Monitoring Technologies Workshop included:

- OP.3: Wolfgang Habel (BAM; ISHMII) provided an overview of SHM in civil engineering.

- OP.6: Glauco Feltrin (EMPA) illustrated the use of data intensive long-term monitoring with wireless sensor networks, using examples of road and rail bridges.

- OP.7: Katerina Krebber (BAM) described the use of optical fibres in technical textiles for monitoring geotechnical and masonry structures.

- PP.2: Vincent Lamour (Cementys) presented a method for monitoring the health of concrete structures used as radioactive waste containers (Lamour *et al*., 2009).

- PP.10: Jean-Marie Hénault (EDF) presented a lifecycle management flowchart for monitoring of nuclear plant structural integrity.

SHM programmes for engineered structures aim to provide:

- An indication of early-stage structural changes.

- Immediate detection of any damage.

- Proof of the integrity and load-bearing capacity of the structure.

- Knowledge to feed into design changes.

SHM systems include the sensors themselves and the strategies for data acquisition, evaluation (e.g. by comparison with models) and decision-making. The sensors need to be tested and validated according to procedures, for example those described in International Standard EN ISO/IEC 17025 (General requirements for the competence of testing and calibration laboratories). Sensor expertise can be adapted to the differing conditions that may be found in a radioactive waste disposal facility compared to a civil engineering structure. Technologies include wireless sensor networks (Section 4.2), fibre-optic sensors (Section 4.3) and micro-seismic monitoring (Section 4.4).

Guidance on the choice of sensors for SHM is available from the International Society for Structural Health Monitoring of Intelligent Infrastructure (www.ishmii.org).

The 5th European Workshop on Structural Health Monitoring will take place in Sorrento in July 2010 (http://www.ewshm2010.eu/) and the 5th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-5 2011) will be held on December 4-8, 2011 in Cancun, Mexico (http://www.ishmii.org/News/SHMII5.html).

The guidance and protocols developed for SHM may provide a useful source of information for the development of repository monitoring programmes.

3.2 Radioactive Waste Storage

Prior to disposal in geological repositories, radioactive waste is likely to be packaged and stored in surface-based interim stores. Many of these stores have been constructed and are in operation. Active monitoring is being undertaken in operating stores, including monitoring of waste package condition and store integrity. The monitoring of radioactive waste stores and the waste packages held within them provide a valuable analogue to monitoring of radioactive waste and engineered barriers in repositories, for example maintaining information on the condition of waste packages and the ability to retrieve packages from a store. Store monitoring is particularly relevant as it has to be conducted in the presence of a radiation field, and, therefore, the radiation tolerance requirements of store monitoring sensors are similar to the requirements on radiation tolerance of repository-based sensors.

Presentations related to monitoring in radioactive waste stores and monitoring of radioactive waste packages at the Troyes Monitoring Technologies Workshop included:

- OP.2: Simon Wisbey (NDA) provided an overview of monitoring practices in radioactive waste stores in the UK.

- PP.2: Vincent Lamour (Cementys) presented a method to monitor the health of concrete structures used as radioactive waste containers.

- PP.16: Werner Daum (BAM) described sensor technologies for monitoring radioactive waste packages and radioactive waste stores.

- PP.17: Jenny Morris (GSL) provided examples of monitoring techniques and sensors used in radioactive waste stores.

In the UK, intermediate-level radioactive waste (ILW) and HLW that has been conditioned for disposal is currently held in thirteen stores, with several more stores planned or under construction. Two other shielded stores hold unconditioned waste in disposal containers. The conditions within surface radioactive waste stores must be suitable for protection of the stores and waste packages from corrosion. This is achieved by controlling temperature, relative humidity and airborne contaminants. The NDA has identified the following monitoring technologies for further development:

- Active coupons with temperature, humidity, corrosion and salt deposition monitoring, and inductively coupled power and communications; these are referred to as SMART coupons.

- Laser Induced Breakdown Spectroscopy (LIBS) for non-contact measurement of salt deposition on surfaces.

- Use of passive intermodulation (induced eddy currents) to inspect lifting features of packages.

- Incorporation of non-radioactive and non-reactive gases (e.g. krypton) into coupons, which are released on corrosion and can be measured as a tracer to indicate the extent of corrosion.

An Integrated Project Team on Interim Storage has been established to co-ordinate work on radioactive waste storage, and intends to publish guidance in 2011 on package and store care and management. Guidance on radioactive waste store monitoring has been developed by NDA (NDA, 2008).

Monitoring of repositories could benefit from further understanding of the techniques currently being considered for monitoring of waste packages in stores. Guidance on store monitoring may provide approaches of use in repositories.

3.3 Mining

In the mining industry, geotechnical monitoring is used to support mine safety, to warn against roof falls and to provide input to design where there is insufficient understanding of the structural performance of the rock mass and support systems. Monitoring systems can be used to measure:

- Rock deformation, using extensometers and visual or electronic "tell-tales".
- Support loads, using strain-gauged rock bolts and vibrating wire strain gauges.
- Rock stress, using an overcoring method such as the CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia) hollow inclusion cell.
- Rock condition and support condition using acoustic energy meters (AEM), "sentinel" rock bolts and radio frequency (RF) parallel tendons methods.
- Fractures induced through mining operations, using microseismic and acoustic emission monitoring.

Monitoring the stability of repository access ways and disposal cells will be an important activity throughout repository operation. The types of monitoring systems used in mines are likely to be useful in repositories.

Presentations related to monitoring of mines at the Troyes Monitoring Technologies Workshop included:

- OP.1: Dave Bigby (Golder Associates) presented a summary of geotechnical monitoring for mine safety and design.

A key instrument used for mine safety monitoring is the dual-height rock-bolting tell-tale. This provides a visual indication of roof movement above and below the rock bolted height. The tell-tales use a traffic light system designed to warn of impending caving (roof collapse) above and below the rockbolted height and are simple, cheap and robust. A UK code of practice specifies that tell-tales should be installed every 20 m in mine tunnels. In a typical installation, data from remote-reading tell-tales are transmitted using up to 100 low-cost transponder units to an underground interrogation unit, which transmits measurements to a personal computer (PC) at the surface.

Displacement of mine roofs and walls is also measured with extensometers and through the use of strain gauge rockbolts (which measure a load profile along their length indicating rock properties and rock stresses around a tunnel).

Rock conditions, in particular the adherence of tunnel linings to rock, can also be measured using a simple AEM, which measures the reverberation decay time in response to hammer signals. Testing of the AEM on rail tunnel linings has indicated that repeatable measurements can be collected, and voids of about 0.2-0.3 m^3 can be detected.

Targets for R&D include improving rockbolt *in situ* integrity testing, developing web server platforms for remote-reading tell-tale systems, developing civil engineering-oriented remote-reading extensometers, and wireless-enhanced mine rescue communication systems.

The discussion of mine safety monitoring highlighted the use of simple and robust monitoring systems that provide both reliability and stability under the environmental conditions to be found underground. These systems will need to be employed in repositories to meet standard health and safety requirements. Monitoring displacement of roof movement will also provide input to the general scientific understanding of the host rock, especially the excavation damaged zone (EDZ) and will feed into long-term safety assessment.

3.4 Carbon Capture and Sequestration

Carbon dioxide can be captured through biological, chemical or physical processes, e.g. as a pure by-product in processes related to petroleum refining or from flue gases from power generation. Carbon dioxide sequestration (or storage) refers to large-scale, permanent artificial capture and sequestration of industrially produced CO_2 using subsurface saline aquifers, reservoirs, ocean water, aging oil fields, or other carbon sinks.

Monitoring of carbon sinks used for carbon capture and sequestration is required to demonstrate that CO_2 is being safely and successfully contained within the sink. The regulatory framework for carbon sequestration is currently under development.

Carbon sequestration provides an analogy to radioactive waste disposal, i.e. the removal of material from the earth's surface and disposal in the sub-surface with isolation and containment of the waste achieved by the host rock. Monitoring the evolution of CO_2 injected into the sub-surface provides an analogue to the monitoring of radionuclide and gas migration following emplacement of waste underground.

Presentations related to carbon capture and sequestration (CCS) at the Troyes Monitoring Technologies Workshop included:

- OP.11: Gareth Williams (British Geological Survey) described quantitative monitoring of the CO_2 injection plume at the Sleipner Field in the North Sea.
- PP.3: Vincent Vanderweijer (TNO) provided an overview of monitoring tools used to monitor current CO_2 sequestration projects.

It is expected that quantitative monitoring of CO_2 sequestration will only be required if there is a qualitative indication of migration of CO_2 away from the sink. However, several issues need to be taken into account to achieve quantitative monitoring:

- The resolution and accuracy of individual monitoring methods.
- The parameters that are measured by the monitoring method.
- The impact of the quantity or concentration of CO_2 on the feasibility of monitoring.

Important aspects also include the spatial sampling of the storage site (the location of the measurements) and the temporal sampling (how often measurements are taken). These issues are also highly relevant to monitoring a geological repository for radioactive waste.

Quantitative monitoring of the Sleipner field has been tested using time-lapse 3D seismic reflection surveys. The volume of CO_2 estimated from analysis of the surveys undertaken in the period 1996-2001 is 15% lower than the volume of CO_2 injected, and indicates the difficulty in developing quantitative monitoring of gases and liquids using current time-lapse 3D seismic surveying. This issue is discussed further in Section 4.3. It is likely that monitoring of CO_2 sequestration sites will use a combination of model-driven, scenario and risk-based monitoring approaches where multiple techniques are used to optimally monitor a CO_2 storage site.

Improvements to seismic imaging of carbon sequestration sites could be made through use of vertical seismic profiles (VSPs) collected through boreholes (in addition to the injection borehole). However, this is considered to represent a problem for the seal integrity of the injection sites, and, therefore, is not currently considered practical.

The sampling strategies applied during monitoring of CO_2 injection sites may be transferable to repository sites, e.g. understanding of the uncertainty in quantitative monitoring, and spatial and temporal sampling strategies.

4. Monitoring Technologies

In this section, we summarise aspects of the presentations at the Troyes Monitoring Technologies Workshop focused on monitoring technologies. Six types of monitoring technology were discussed:

- Wireless sensor networks and wireless through-the-earth data transmission (Section 4.1).
- Fibre-optic technologies (Section 4.2).
- Geophysical techniques (Section 4.3).
- Monitoring of groundwater and chemistry (Section 4.4).
- Geotechnical monitoring (Section 4.5).
- Air-based and satellite-based monitoring (Section 4.6).

For each type of monitoring technology:

- A high-level summary of the monitoring technology is provided.
- Presentations related to the technologies are listed, and a reference given to the abstract number (OP refers to oral presentations, which can be found in Appendix D, and PP refers to poster presentations, which can be found in Appendix E).
- The discussions at the workshop are summarised.

4.1 Wireless Sensor Networks and Wireless Through-the-earth Data Transmission

Wireless sensor networks (WSNs) consist of spatially distributed autonomous sensors used to monitor structures and/or environmental conditions (Römer and Friedemann, 2004). 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.

WSNs and through-the-earth data transmission are of interest to repository monitoring as these technologies may provide the ability to monitor the near-field of the repository system non-intrusively.

Presentations at the Troyes Monitoring Technologies Workshop in which WSNs were discussed included:

- OP.6: Glauco Feltrin (EMPA) described the use of WSNs in the field of structural monitoring. He described examples of the monitoring of bridges using WSNs.
- PP.14: Jose-Luis Garcia-Sineriz (Aitemin) described the state-of-the-art for wireless sensor and transmission networks.

- PP.16: Werner Daum (BAM) presented a special self-configuring, multi-hop wireless sensor network system designed for long-term monitoring of buildings or engineering facilities.

Each node of a WSN is a box containing sensors attached to a data acquisition unit, a Central Processing Unit (CPU) and memory, a power supply (batteries), and an RF-transceiver for communication. The software is as important as the hardware as it enables network functionality, task scheduling and remote maintenance. Feltrin (OP.6) reported that system reliability (~99%), stability and accuracy are sufficient for most civil engineering applications.

Supplying power to nodes is a challenge for long-term operation of WSNs and, with the use of existing batteries, currently limits the remote operating life of the sensors to less than two years. To conserve power, components are switched off when not in use. The quantity of data transmitted may be reduced through the use of data processing methods (transmission of information rather than data), which can provide 100-fold reductions in the power required. Extension of battery lifetimes could lead to the lifetime of WSNs being controlled by the lifetime of the electronics and software. The long-term performance of electronic components has not been tested. There is a potential for the software used in WSN nodes to be re-programmed, but this must be demonstrated. Feltrin (OP.6) stated that these restrictions could limit the lifetime of WSNs to ten years in the future.

Another disadvantage is the physical transmission of data. The range of existing wireless sensors in air is up to 80 m with the RF-transceiver on full power; although this reduces to 20 m with obstructions; line of sight is not required. A relay node can be incorporated to transmit data between the monitoring nodes and the root node (data sink) to increase the range of the network (multi-hop routing).

Experience of the underground application of WSNs was obtained during the Researching the Applications of Open Innovative Wireless Technologies (RAINOW) project, completed two years ago, which used distributed wireless networks in coal mining. High-functionality wireless sensors for harsh conditions are being developed as part of the Integrated Safe and Smart Built Concept (I-SSB) Project, which aims to develop houses for earthquake zones.

Feltrin (OP.6) recognised the following main advantages of WSNs for civil engineering:

- Fast deployment, as boxes can be placed in the right locations.
- Nodes can be added, moved or removed during monitoring as WSNs are auto-configuring.
- Little interference with surroundings; WSNs do not require cables which could obstruct other work such as ongoing construction.

Wireless through-the-earth data transmission provides another aspect of wireless transmission technology having a potential application in geological disposal (Malan *et al.*, 2000). Research specifically focuses on through-seal and/or through-the earth transmission, to provide a tool allowing to pursue some amount of data acquisition from sensors in sealed repository areas. Transmission is envisioned both to a receiver placed in an accessible part of the repository, or to a received placed on the surface.

Transmission of monitoring data through geological media is especially challenging. High-frequency electromagnetic waves (e.g. ~100 MHz) are highly attenuated by rocks. R&D undertaken to this end through radioactive waste disposal projects (PP.14; PP.19 and PP.20) is using electro-magnetic pulses, very-low-frequency electro-magnetic radio waves ("through-the-earth radio") and very-low-frequency magneto-induction to transmit data.

Presentations at the Troyes Monitoring Technologies Workshop in which wireless through-the-earth transmission were discussed included:

- PP.19: Yasuhiro Suyama (RWMC) described the development of wireless transmission monitoring within the context of geological disposal of radioactive waste.

- PP.20: Thomas Schröder (NRG) described research being undertaken to improve transmission of monitoring data through rock from depths of 500m to the surface.

The current state-of-the-art in WSNs and through-the-earth data transmission is insufficient for meeting the requirements of repository monitoring, owing to the limitations of power supply and through-the-earth data transmission. Research into these issues will be conducted as part of the MoDeRn Project and is also being undertaken outside of the radioactive waste management industry.

4.2 Fibre Optic Sensors

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).

Optical fibres may be selected for monitoring because of the small size of the fibres, because no electrical power is needed at the remote location, or because 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.

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 (LEDs)).

Optical fibres have a wide range of potential applications because they can operate under harsh environments, including environments with:

- Strong electro-magnetic fields.

- High temperatures.

- Explosive potential.

- Aggressive chemical species.

- Ionising radiation.

Presentations at the Troyes Monitoring Technologies Workshop in which fibre optic sensors were discussed included:

- OP.3: Wolfgang Habel (BAM) illustrated his presentation on civil structural monitoring with examples of the application of optical fibres.
- OP.7: Katerina Krebber (BAM) described the incorporation of optical fibres in technical textiles and described the benefits of polymer optical fibres (POFs).
- PP.13: Jan Verstricht (Euridice) presented the use of fibre optic sensors for monitoring of the HADES underground research laboratory.
- PP.15: Phillipe Renaud-Goud (UTT) presented research into optical sensor systems being conducted on behalf of Andra.

Fibre optic sensors can be used to monitor single locations or as distributed sensors, where events can be detected and located with a spatial resolution of one metre along the fibre axis. Krebber (OP.7) described distributed sensor networks in which optical fibres have been incorporated in technical textiles, such as geotextiles used for reinforcement of earth embankments. Both POFs and glass (silica) optical fibres have been incorporated into technical textiles.

A key aspect of research to date has been the attachment of the sensors to the textile as failure to properly attach the fibres into the textile can lead to poor signals owing to noise and localised bending, and, if the fibre is improperly attached, measured fibre deformation would not be representative of deformation of the geotextile. Research is currently focusing on embedding fibres rather than attaching the fibres to textile surfaces. Detection of strain is ensured by incorporating a relatively high-density grid of fibres into the textiles.

Owing to their elastic properties, polymer optical fibres can detect high strains. Krebber (OP.7) showed examples where local strains of 20% have been measured by POFs. Glass optical fibres can only measure strains of less than 1% owing to the brittle properties of the glass fibres. Further research is required on the visco-elastic (creep) properties of POFs as research has indicated a measurement error of 0.5% when using POFs.

When compared to conventional geotechnical sensor systems, POF systems are expected to reduce costs by 20 – 40 % (an example was given of 96,000 m^2 of the Katabenz highway, where monitoring using conventional single sensors costs \$65/m^2 and monitoring using a single distributing sensor costs \$25/m^2). The length of a standard POF is limited to 100 m by high attenuation; low-loss fibres are designed to operate on a wavelength of 1.3 µm to extend the distance and dynamic range, but are not currently commercially available with a durable jacket. Krebber (OP.7) stated that distances in excess of 500 m are likely to be achieved with further research.

During R&D on fibre-optic pH sensors, membrane stability problems included leaching, washing out, mineralisation and crystallisation on the surface of the membrane. These problems have been addressed and tests (over 5 years) have shown fibre optic pH sensors to be stable for more than three years.

Guidance on the choice of fibre-optic sensors is available from:

- The FIDES (Optical Fibres for New Challenges Facing the Information Society) project (www.cost299.org).

- Guideline VDI/VDE 2660 Part 1 (Experimental stress analysis - Optical strain sensor based on fibre Bragg grating - Fundamentals, characteristics and sensor testing), available from www.beuth.de.

- A new project on "Novel and Reliable Optical Fibre Sensor Systems for Future Security and Safety Applications" starts in September 2010.

Fibre optic sensors have significant potential for deployment in repository engineered barrier systems but issues related to deployment over long periods and spatial determination of strain require further research.

4.3 Geophysics

Several geophysical techniques exist for monitoring geological processes and the evolution of engineered structures. At the Troyes Monitoring Technologies Workshop, the following geophysical technologies were discussed:

- Seismic interferometry. Seismic interferometry 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. A presentation on seismic interferometry was given by Andrew Curtis (University of Edinburgh) (OP.10).

- Time-lapse 3D seismic. Seismic reflection surveys provide information on the velocity structure of the sub-surface by recording the reflection of a known seismic source. Time-lapse 3D seismics can be used to provide an understanding of the movement of fluids (European Association of Geoscientists and Engineers, 2003). Gareth Williams (British Geological Survey) presented a summary of the use of time-lapse 3D seismic surveying to monitor the injection of CO_2 into the Sleipner gas field in the North Sea (OP.11).

- Acoustic emission and microseismicity monitoring. Acoustic emissions and microseismic surveys monitor fracturing in rock and man-made materials through measurement of the seismic signals emitted when materials fracture (Young and Martin, 1993). Juan Reynes-Mentes (Applied Seismology Consultants) gave an overview of acoustic emission and microseismicity monitoring (OP.12 and PP.22).

These techniques may be applicable to monitoring of the response to repository construction and operation, including evolution of the engineered barrier system (seismic interferometry), migration of radionuclides and repository-derived gases (time-lapse 3D seismics) and the rock mechanical response of rock close to disposal cells and access ways (e.g. development of an EDZ).

Interferometry

Seismic interferometry is a technique which uses seismic "noise" in place of active seismic sources to create virtual sources. The "noise" energy that passes through two receivers A and B is cross-correlated to produce the seismogram that would have been detected at B had there been a source at A.

Surveys are designed in the same way as active seismic surveys, with receivers placed apart at distances of more than half a wavelength; therefore, the monitoring of low-frequency noise requires a larger separation between receivers than the monitoring of high-frequency noise. Remote monitoring of changes in a tunnel using seismic interferometry would require receivers to be placed in boreholes approximately 100 m from the tunnel with current technologies and interpretation techniques.

Coda wave interferometry takes scattered late-arriving waves (coda waves), which contain more information about seismic properties, and compares the shape of the wave tails to determine velocity changes over time. At present, the spatial resolution of coda wave interferometry is low, but research is being conducted to improve spatial resolution through an understanding of the velocity structure of the volume under investigation.

The theory of differential equations for seismic interferometry can be applied to electromagnetic and electrokinetic interferometry, which are emerging fields in geophysics.

The state-of-the-art in seismic interferometry is not yet ready to be applied to repository monitoring, but there has been little research on application of seismic interferometry in repository programmes.

Time-lapse 3D Seismics

Approximately 11 million tonnes of CO_2 have been injected into the 200-m thick Utsira Sandstone formation of the Sleipner CO_2 injection site, which is located in the North Sea off the coast of Norway. Time-lapse 3D seismic surveys have been used to monitor the injection of CO_2 into the Utsira Sandstone. Research projects have investigated methods of quantifying the volume of CO_2 trapped within the Utsira Sandstone using the time-lapse 3D seismic data. The objective is to demonstrate the quantitative monitoring of CO_2 migration following injection.

Time-lapse seismic surveys have been acquired in 1999, 2001, 2002, 2004, 2006 and 2008, and have proven to be successful in imaging the growth of the CO_2 plume. However, an attempt to match the volume of CO_2 imaged against the volume of CO_2 injected results in a mis-match of 15% (an under-estimate of the volume of CO_2 imaged). This mis-match may be the result of uncertainties in the behaviour of the CO_2 (e.g. dissolution of CO_2 in formation water), uncertainties in reservoir properties (e.g. assumed reservoir temperature), and may also be the result of uncertainties in the interpretation of the seismic surveys caused by:

- The reduced reflectivity of horizons containing CO_2.
- Uncertainty in the amplitude models used for interpretation.
- The difficulty of imaging lower layers due to attenuation of signals by CO_2 in upper layers.

Spectral decomposition of seismic data is the characterisation of the time-dependent frequency response of subsurface rocks. Spectral decomposition of seismic data and reservoirs can potentially be used to enhance the vertical resolution within the Utsira Sandstone to improve the quantitative monitoring of the CO_2 injection and migration. The imaging of the CO_2 plume could also be improved by using vertical seismic profiling, but, as this would require the drilling of a well to allow introduction of a seismic source, this is considered impracticable in Sleipner (the well would act as a pathway for CO_2 migration).

Gas production rates in repositories are likely to be significantly lower than the volumes of gas that are being injected into the Utsira Sandstone in the Sleipner Field. This may make the use of time-lapse 3D seismics to monitor gas generation and migration in repositories impractical. In addition, the properties of the Utsira Sandstone (high compressibility of the rock and a high contrast in fluid properties) are highly suited to imaging using reflection seismics. Therefore, the ability to use time-lapse 3D seismic surveying for monitoring gas generation and migration in a repository setting depends on site-specific factors.

Time-lapse 3D seismic surveys are becoming a standard technology in the oil and gas industry in order to monitor the production of oil and gas from the sub-surface. However, this application is generally limited to high-porosity, and high-permeability stratigraphic sequences, not low-permeability rocks considered for disposal of radioactive waste. Application of the state-of-the-art in time-lapse 3D seismic surveying would require demonstration of the technique in a specific repository environment, and would also depend on the expected evolution of the repository system (e.g. rate of gas production from corrosion of metals).

Acoustic Emissions and Microseismicity

A microseismic event involves the rapid release of stress and accumulation of strain owing to brittle failure, in which sonic energy is emitted in the frequency range 50 Hz to 10 kHz. The frequency range of acoustic emissions is >10 kHz. Acoustic emissions and microseismic (AE/MS) events are caused by opening and shear of fractures and pre-existing structures and can be stimulated by:

- Stress changes.
- Pore pressure changes.
- Volume changes.
- Application or removal of a load.
- Some combination of the above.

The magnitude and nature of the stress change must be large enough to result in failure. In suitable geological conditions, AE/MS can be used to detect failure at the granular level. Human activity can either directly induce or indirectly trigger seismicity. Monitoring of stimulated seismicity can provide feedback on the engineering performance of a site or infrastructure.

The scope and detection characteristics for an AE/MS survey are limited by the design of the array of seismometers. Active sources can also be used for calibration or to build a more complex model. Microseismic techniques have been applied in the civil engineering, petroleum, geothermal energy, CO_2 sequestration and mining industries, for example:

- Real-time monitoring and optimisation of hydrofracture stimulations in petroleum fields, chemical or thermal stimulation of geothermal fields and monitoring of reservoir integrity during CO_2 injection.

- Fracture mapping to provide information on feasibility of target volumes for new development wells.

- Validation and development of numerical models for predictive modelling of repository behaviour.

- Detection of active fault zones, fractures, compaction and subsidence in and around engineered structures and delineation of potential fluid pathways.

- Safety monitoring of structures, tunnels and underground spaces, to provide early warning systems.

It is known that AE/MS activity is generated during rock failure, both in the laboratory and within the mining environment. The construction of a repository in the underground environment will lead to a redistribution of stress and strain energy, and is likely to cause induced seismicity to occur on a number of scales, particularly on pre-existing faults and fractures, although the excavation of the facility will also generate new fractures. Microseismic techniques are less suitable for use in host rocks with plastic properties (e.g. unconsolidated clays) owing to an absence of brittle failure and the frequency of sonic episodes where brittle failure does occur, and, therefore, the applicability of the state-of-the-art to repository environments depends on site-specific conditions.

The same types of sensors can be used for microseismic monitoring and seismic interferometry and the two techniques are complementary.

4.4 Monitoring of Groundwater and Chemistry

Groundwater flow and chemical conditions can have a significant impact on the long-term safety of geological repositories. Understanding of groundwater flow and the chemical environment may therefore be important components of a repository monitoring programme (Domenico and Schwartz, 1998). Completion systems for deep boreholes provide a means for deploying networks of sensors for far-field hydrogeological monitoring. Such systems provide considerable versatility for testing and characterisation, quality assurance testing to confirm system and data integrity, and removal and replacement of sensors for servicing and maintenance over the long term. In addition, other sensors can be deployed as they become available in the future.

Presentations on the monitoring of groundwater and chemistry at the Troyes Monitoring Technologies Workshop included:

- OP.4: Bill Black (Schlumberger) described the Westbay system used for characterising and monitoring groundwater.

- PP.4: Jonathan Marsh (Golder Associates) described the use of multi-packer systems for long-term hydraulic monitoring at the Bátaapáti Repository in Hungary.

- PP.11: David Conroy (University of Leeds) described the use of biosensing for detecting groundwater contamination by uranium.

- PP.12: Peter Morris (Salamander) described the development of GasClam, a continuous gas monitoring device.

Monitoring of hydraulic head profiles at multiple depths can be conducted by inserting sensors into boreholes with multiple monitoring points hydraulically isolated from each other by packers inflated with water or other incompressible fluids. The placing of the monitoring points is typically undertaken with respect to a conceptual model of the hydrogeological regime. Recent advances in groundwater monitoring systems include the ability to emplace larger numbers of monitoring points than has historically been the norm. This provides greater flexibility in the nature of data collected from any particular borehole and the ability to produce more detailed profiles of fluid pressure measurement through a given geologic sequence.

Other developments in groundwater monitoring systems include extending multiple completion methods to depths of ~2,400 m and the upgrading of instrumentation to allow measurement of pressures up to 5000 psi.

The state-of-the-art in groundwater monitoring has been developed in close collaboration with radioactive waste disposal programmes. As a consequence, the state-of-the-art closely reflects the requirements of repository monitoring.

4.5 Geotechnical Monitoring Technologies

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 and may lead to the modification of repository designs.

Presentations on geotechnical monitoring at the Troyes Monitoring Technologies Workshop included:

- OP.1: Dave Bigby (Golder Associates) presented a summary of geotechnical monitoring for mine safety and design.
- OP.5: Rainer Glötzl (Glötzl GmbH) described the main stress technique for monitoring rock stress.
- OP.8: Erik Wolfart (JRC) described the use of laser scanning for monitoring the as-built status of the ONKALO facility in Finland.
- PP.5: Martina Ligaunova (Rawra) described the monitoring of the closure of three disposal chambers at the Richard Repository in the Czech Republic.

Geotechnical monitoring technologies presented by Bigby (OP.1) were discussed in Section 3.3.

The Main Stress Technique for Monitoring Rock Stress

The Glötzl multiple point extensometer system can be used to provide direct stress measurements as an early alert that future deformations (measured by the extensometer) will happen, with each sensor comprising optical fibres, a diaphragm and two interferometers. The second interferometer provides an intrinsic correction for drift so that the sensors do not need to be recalibrated. Although corrosion of the sensor is a potential problem for long-term installations of the extensometer, no drift has been detected as a result of corrosion in systems installed to date. The system measures total pressure and is unable to separate fluid and effective stress. Measurement of stress and deformation helps to provide a more complete understanding of the geomechanical development of the rock surrounding underground excavations.

Glötzl multiple point extensometer systems have been installed in clay, salt and coal. The system was tried unsuccessfully in a borehole in the HADES URL at Mol, Belgium; issues with the installation included coupling of the system with the host rock (i.e. grouting the system into a borehole) and the standard problem that drilling a hole in rock disturbs the stress field. Salt concrete and resin injection have been tested for grouting the system into other rock masses.

Stress determination and monitoring is important for the design, construction and operation of repositories, and the approaches used in mines worldwide will be suitable for repository monitoring.

Laser Scanning

A range of time-of-flight-based laser scanners can be used to produce 3D models of the geometry of excavations, with different scanner types having a maximum distance of 100 to 1000 m with a spatial resolution of 5 mm and accuracy of 5-10 mm. A laser scanner was demonstrated in a tunnel at the ONKALO underground characterisation facility, Finland, for comparison against a Computer-aided Design (CAD) model and to verify the design. The 3D model included 3.6 billion discrete measurement points at 6 mm intervals. Current research areas include new methodologies for managing the large amounts of data which are generated through 3D laser scanning.

The accuracy of laser scanning is sufficient for repository monitoring applications.

4.6 Air-based and Satellite-based Technologies

Monitoring of the surface of repositories can be undertaken using air-based and satellite-based systems to develop an understanding of the changes to the surface as a result of repository development and to monitor for unexpected activity. Presentations on air-based and satellite-based monitoring technologies at the Troyes Monitoring Technologies Workshop included:

- OP.8: Erik Wolfart (JRC) described imaging of facilities at Olkiluoto, Finland.
- OP.9: Ren Capes (Fugro NPA) described the state-of-the-art in satellite radar interferometry (InSAR).
- PP.19: Thomas Häme (VTT) described the use of satellite and airborne remote sensing for the provision of safeguards.

Imaging

Satellite images (Campbell, 2002) have been used for over 10 years in monitoring activities associated with the Treaty on the Non-Proliferation of Nuclear Weapons (the non-proliferation treaty (NPT)). Most monitoring is based on comparison of site plans with optical images with a resolution of up to 50 cm; synthetic-aperture radar (SAR), thermal and hyperspectral images are other imaging technologies that could be applied. As part of the EC Land and Sea Monitoring for European Security (LIMES) project, software was developed for integrated presentation of information from different sources and for increased automation of the image processing workflow. The software uses a time-series of images taken of the same area and highlights changes in different colours.

The main advantages of SAR compared to optical images are that it works in all weather and at night, and provides ground movement and 3D information (height information is extracted from stereo-pairs of images and differences seen over time); the disadvantage is that the images are more difficult to interpret.

Imaging is most likely to be applied in monitoring for safeguards purposes, and the state-of-the-art is sufficient for such applications.

Radar Interferometry

Interferometric synthetic aperture radar (InSAR) can be used to measure changes in surface elevation through measurement of the phase change in reflected radar signals (Ketelaar, 2009). Radar signals have a wavelength of approximately 5.6 cm. Three types of InSAR are available:

- Differential InSAR (referred to as DifSAR or imaging InSAR).
- Persistent Scatterer InSAR (PSI).
- Corner Reflector InSAR (CRInSAR).

DifSAR requires three radar images to develop a differential image between pairs of the images (a scene-pair). DifSAR images may be affected by atmospheric artefacts. Vegetation cover disrupts correlation of images, and, therefore, DifSAR works better in built environments. The cost of DifSAR is approximately €7,000 per scene-pair (the area of a scene-pair is 100×100 km). An additional scene-pair is €3,000.

Persistent Scatterer Interferometry (PSI) overcomes atmospheric diffraction by processing stacks of images (minimum of 30 images) using an algorithm that looks for reflecting features that are repeated in each image. PSI makes measurements of ground movement on naturally occurring permanent scattering points. Persistent scatterers are features such as the roofs of buildings, metallic structures and prominent natural features. Validation of the PSI technique was undertaken under the auspices of the Terrafirma project (www.terrafirma.eu.com). The cost of a 10-15 year stack of >100 images is approximately €40,000 and would cover an area of 50×50 km.

CRInSAR makes measurements from radar satellites to tetrahedral corner reflectors that are secured to the feature on the ground to be monitored. CRInSAR provides millimetre-scale accuracy. This system is not suitable for monitoring displacement of road surfaces because of specular reflectance. The cost of system set-up is approximately €4,000 for ten reflectors. Analysis of ground motion costs €9,000 for the first three passes and €3,000 for subsequent passes.

Monitoring of surface elevation changes on a mm-scale would provide significant understanding of a range of sub-surface processes linked to the long-term performance of repositories and is likely to be an important repository monitoring technology in most national programmes.

5. Discussion

The Troyes Monitoring Technologies Workshop gathered 55 experts from a range of organisations, including industry, radioactive waste management organisations and research institutes. The workshop provided an opportunity for communication between these different groups.

Participants with little knowledge of radioactive waste disposal prior to the workshop commented that the workshop had provided an excellent opportunity to learn more about this subject, and the requirements and constraints on monitoring geological repositories. Participants working in radioactive waste disposal were provided with an opportunity to identify new developments in monitoring technologies across a broad range of disciplines. Ten EC projects with a monitoring component were discussed (listed in Appendix C).

Knowledge transfer was facilitated through several means:

- Discussions on specific monitoring technologies at the end of each oral session.
- Extended poster sessions.
- A round-table discussion that was held at the end of the workshop, and which discussed the following issues:
  - The state-of-the-art for each of the technology areas discussed at the workshop.
  - Potential for technology transfer between areas of application (in particular knowledge transfer to monitoring associated with radioactive waste disposal projects).
  - Identification of key issues for R&D on monitoring technologies.

This section summarises the round-table discussion and draws out key points raised during the discussions at the end of each section of the workshop. It is not intended as a comprehensive summary of repository monitoring, but as a record of workshop discussions.

This section is structured in the format used for the end-of-workshop round-table discussion:

- Section 5.1 summarises conclusions regarding the state-of-the-art of monitoring technologies as identified at the Troyes Monitoring Technologies Workshop.
- Section 5.2 discusses the potential for technology transfer.
- Section 5.3 summarises R&D requirements identified at the workshop.

5.1 State-of-the-Art in Monitoring Technologies

The state-of-the-art in monitoring is a rapidly evolving position, and R&D is constantly extending the capabilities of monitoring technologies. Conclusions regarding the state-of-the-art for the various types of monitoring presented at the Troyes Monitoring Technologies Workshop are as follows:

- Wireless sensor networks (WSNs): Battery power limits the operation of WSNs to 1-2 years. Data processing techniques can reduce the quantity of data requiring transmission by 99%, which may lead to increasing effective operating time to 10 years.

- Wireless through-the-earth transmission: Current developments suggest the feasibility of direct transmission of a limited amount of data from the repository to the surface, over a period of one or several decades.

- Fibre optic sensors: Fibre optic sensors are available for the measurement of temperature and strain, with some capability for measuring these parameters on a distributed basis. Glass optical fibres can measure strains of 1%, whereas polymer optical fibres can potentially measure strains up to 40% and have been demonstrated to measure strains up to 20%.

- Seismic interferometry: Developments in coda wave analysis allow for the monitoring of temporal changes in the average properties of a medium (e.g. pressure as a result of thermal expansion) of ~0.1% – 0.01%.

- Time-lapse 3D seismics: Estimates of the volume of CO_2 imaged on 3D seismic surveys of the Sleipner Field in the North Sea accounts for 85% of the injected CO_2.

- Acoustic emissions and microseismicity (AE/MS): AE/MS events have been monitored in response to changes in pressure (of 4 MPa) and changes in temperature (of 6°C) in underground research laboratories.

- Borehole multiple completion methods for fluid pressure measurement have recently been extended to depths of ~2,400 m and instrumentation has been upgraded to allow measurement of pressures up to 5000 psi.

- Strain monitoring using extensometers and tell-tales: Tell-tales can monitor millimetre-scale displacements in tunnels.

- Stress monitoring: Installation of multiple point systems prior to tunnel excavation can detect the impact of excavation on the *in situ* stress up to 100 m from the tunnel. Monitoring of coupled stress and deformation in a range of underground settings has illustrated that stress can be used as a good indicator that deformation might happen; a sensor has been developed that auto-corrects its “0” point.

- Laser scanning: Laser scanning has been used to develop 3D models of underground excavations that can resolve features as small as 5 mm in diameter, with 3-5 cm spatial accuracy, when the laser scanning devices are placed up to 1 km from the target.

- Satellite imagery: Optical imaging technology is readily available with a 50 cm resolution.

- Radar interferometry: CRInSAR provides millimetre-scale monitoring of changes in ground elevation.

The values quoted above are relevant to the environment in which the monitoring was undertaken. Alternative views of the state-of-the-art may be available elsewhere, or may be relevant for different environments.

Developments in the state-of-the-art in monitoring technologies will be undertaken in the MoDeRn Project. These will include:

- Improving the range of low-frequency based wireless through-the-earth transmission.
- Adapting ZigBee and similar wireless sensor nodes and transmission network to the repository environment.
- Development of remote, wireless energy transfer to recharge batteries.
- Improving the resolution of geophysical monitoring techniques, in particular through the development of improved waveform analysis tools.
- Developing Brillouin scattering fibre optic sensors for use in a heated gallery.
- Developing short and long-term monitoring of cement-based grout, combining time-domain reflectometry (TDR), deformation gauges and ultrasonic characterisation.

In addition, demonstration and development of wireless and non-intrusive monitoring techniques will be undertaken. These activities will be applied to monitor mock-ups that equate to repository conditions and allow typical parameters from these mock-ups to be monitored. The mock-ups will be developed in underground research laboratories (URLs): the Grimsel Test Site, the HADES URL and the Bure URL. The mock-ups will include work on battery life extension and providing energy remotely. The development of battery life extension and the possibility of providing energy remotely to isolated sensors is being addressed. Therefore, work in the MoDeRn Project will contribute to the state-of-the-art in monitoring technologies.

5.2 Knowledge Transfer to Radioactive Waste Disposal

Repository Requirements and Constraints

The Troyes Monitoring Technologies Workshop described and discussed a broad range of techniques that may be suitable for monitoring of geological repositories. The state-of-the-art in various types of monitoring was discussed and aspects of the state-of-the-art identified for particular environments. However, geological repositories have specific constraints, particularly the thermal, hydro, mechanical and chemical (THMC) conditions under which monitoring sensors must operate, and the timescales over which monitoring is required. In addition, monitoring of a repository must not affect the long-term safety of the disposal system (IAEA, 2006b).

Environmental conditions are dependent on the geological disposal concept implemented (e.g. the thermal output of the waste and the quantity of cement used in the EBS). Particular challenges for extended monitoring include temperatures up to 100°C, pressures of 30-40 bars, highly alkaline environments (pH ~12.4) and radiation equivalent to a dose of 6 MGy. The

Troyes Monitoring Technologies Workshop recognised that the oil and gas industry does have downhole technologies for working in aggressive environments and that these may be suitable for monitoring of geological repositories.

Repository projects typically extend over many decades and, although there will be opportunities for maintenance of some monitoring systems, other monitoring systems may have to operate without maintenance (although not indefinitely). The long timescales of repository projects mean that simple, robust and well-established/understood systems, such as techniques used for monitoring mine safety (Section 3.3), may be the most appropriate for long-term repository monitoring.

The long-term stability and reliability of all sensors in repository conditions remain to be established and is a particular challenge for successful repository monitoring. It is not just the long-term performance of sensors that is significant for long-term monitoring. The design life of an instrument is also dependent on the mean life to failure of the electrical components. Repository monitoring strategies may be developed where EBS and geological processes can be monitored remotely, in which case long-term power supply to the monitoring equipment is an issue requiring further R&D.

In a repository setting, the practical implications of sensor installation also need to be considered. Protecting the sensor area from chemicals and moisture is an issue in some applications, and physical and material problems can occur where sensors are attached to other components. For long-term monitoring, the repeatability of active monitoring (e.g. seismic tomography) must be established and requires suitable coupling of the seismic source to the medium under investigation. This issue may be overcome by advanced processing techniques such as those employed by interferometry.

Technologies for Repository Monitoring

A substantial range of techniques exists that could be adapted to specific repository conditions and incorporated in repository monitoring programmes. Techniques that could be readily transferable include satellite-based interferometry for monitoring of ground elevation. Repository monitoring programmes typically include a requirement to monitor ground elevation changes in response to repository excavation (subsidence) and as a result of the thermal impact of waste on the host rock (uplift). Nagra has been developing remote sensing techniques collaboratively with the University of Freiburg. Satellite-based monitoring can be used to help maintain safeguards over fissile material.

Non-intrusive measurement techniques and robust, simple *in situ* sensors may be applicable to monitoring of the near field because, following emplacement of waste and the local EBS, it will not be possible to access the disposal cells. However, the technologies that will be used in any specific repository will be dependent on the national context, including the relevant regulations, the nature and quantities of the waste to be disposed of, the repository design, the geological environment and stakeholder expectations.

For certain repository monitoring technologies, the state-of-the-art is already being developed through repository programmes, and in some cases, the radioactive waste management industry appears to be the leader in the field of monitoring technologies. Examples include the sub-surface *in situ* sampling of groundwater chemistry and microbial populations in low-permeability and saline groundwater environments, and developments in through-the-earth transmission of monitoring data (see Section 5.3.2).

Developments in through-the-earth transmission of monitoring data are being undertaken in the MoDeRn Project. These include research into low-frequency based through-the-earth transmission, adapting ZigBee and similar wireless sensor nodes and transmission networks to typical repository environments, and development of remote, wireless energy transfer to recharge batteries.

Staged Decision Making

Repository programmes are typically segregated into stages, including site investigation, repository construction, operation, closure and post-closure (these phases may overlap and be different in different programmes). A key aspect for repository monitoring programmes is determining how to apply monitoring techniques during the staged development of a repository.

There will be major decision-points within a repository programme (e.g. selection of the repository site, defining the layout of the repository, undertaking construction, commencing disposal, moving to closure and ending institutional control). Monitoring will support decisions at all of these steps. Selection of monitoring technologies can be facilitated by an understanding of the key data required for decision making. Repository monitoring programmes will take account of the specific context under which they are undertaken, and value would be provided to waste management organisations if generic approaches to monitoring were developed as part of the MoDeRn Project.

Some programmes have specific monitoring stages within their programmes - for example, there is a federal requirement in Switzerland that confidence is developed in the disposal system through monitoring in a pilot facility. Monitoring technologies to be applied in this situation may be different to those that could be applied in other parts of the repository.

Staged development of repositories offers additional opportunities for monitoring programmes. Direct access to the rock during the construction and operational phases may allow detailed characterisation of the rock (e.g. detailed 3D mechanical understanding including mapping of the fracture systems and development of a 3D understanding of seismic anisotropy), which can be utilised during later stages of the programme when only non-intrusive monitoring would be possible.

An impact of the staged development of repositories is that the requirements on monitoring at each stage will be different. It is possible that monitoring will be more intensive during the early stages of repository implementation, for example, when the understanding of the system is being developed prior to licensing. In the later stages, it is expected that repository monitoring will be more confirmatory and less intensive.

The long timescales over which monitoring may be required also means that the state-of-the-art will evolve during the implementation of repository monitoring. This may mean that more detailed monitoring information can be acquired in the future, but monitoring programmes cannot assume that this will be the case.

Monitoring and the Safety Case

Monitoring can be used to provide information in support of the safety case presented prior to operation of the facility. Long-term safety must not be reliant on monitoring, although monitoring may be required to demonstrate that the assumptions in the safety case are appropriate and that the disposal system is performing as expected (performance confirmation).

Several of the technologies presented at the Troyes Monitoring Technologies Workshop were focused on monitoring of structures that may have a single failure mode. Repository post-closure safety is provided by means of multiple safety functions (IAEA, 2006b). That is, safety is provided by means of multiple barriers whose performance is achieved by diverse physical and chemical processes. A monitoring programme focused solely on a single barrier would be insufficient for a geological repository.

Processes in repositories are highly coupled, and, therefore, monitoring technologies can be applied for monitoring one parameter as a surrogate for another (e.g., the use of SAR to provide data for coupled modelling of thermal and hydrogeological impacts on surface uplift). It was recognised that combining data from monitoring using different technologies (data mining and data fusion techniques) may provide significant added value to a monitoring programme.

It is important to establish protocols for interpreting data and strategies for responding to unexpected monitoring results, because understanding how data feed into the decision-making process will provide confidence to stakeholders.

5.3 Research and Development on Monitoring Technologies

Waste management organisations do not in many cases have the resources to develop new technologies on their own, and the workshop provided a good opportunity to communicate particular requirements of repository monitoring applications to academics, research institutes and commercial organisations, and to identify areas of development to take forward together. It was recognised that some developments responding specifically to technical requirements and constraints of repository monitoring – e.g. longevity of reliable monitoring and non-perturbation of the barriers – must be carried forward by waste management organizations.

Areas for improvement in existing technologies were identified during the workshop and participants agreed that there is a broad range of developments that can be undertaken in the near future. This section summarises the R&D topics identified at the workshop:

- Section 5.3.1 describes the R&D topics related to each of the technologies discussed at the workshop. This R&D is most likely to be led by academics, research institutes and commercial organisations, in some cases with direction and funding from waste management organisations.

- Section 5.3.2 describes R&D topics that will be taken forward in the MoDeRn Project.

5.3.1 General R&D on Monitoring Technologies

Academics, research institutes and commercial organisations are engaged on R&D on monitoring technologies. Identified R&D for the various types of monitoring presented at the Troyes Monitoring Technologies Workshop included:

- Wireless sensor networks (WSNs): In the mining industry, significant research is being undertaken on the development of wireless enhanced mines rescue communication systems. The compressive sampling field of mathematics (being developed at Rice University in the US), which involves randomly sampling time-series data, could be applied to the reduction of data volumes for transmission by wireless networks. The reliability of WSNs is a key topic for ongoing R&D.

- Fibre optic sensors: Fibre optic sensors need to be adapted or developed to suit the environment in which they will be used. R&D is being undertaken to optimise monitoring units (i.e. to make them smaller, cheaper and more flexible). Other R&D topics recognised included:

    - Use of LEDs as a light source for fibre-optic sensors.

    - Use of low-loss polymer fibre-optic sensors, including development of protective jackets, improved understanding of creep and longer-term behaviour of polymer fibres.

    - Systems to allow one device to receive inputs from several optical fibres.

    - Radiation-hardening of polymer optical fibres.

    - Further development of techniques to embed fibre optics in technical textiles.

- Seismic interferometry: A key R&D topic for interferometry is development of interpretation algorithms for application using electromagnetic and electrokinetic waves. Research in this area is being conducted at Delft University.

- Time-lapse 3D seismics: Work on coupled fluid-flow and geomechanical models to understand surface uplift/subsidence in response to CO_2 injection, and oil and gas production is being undertaken by Lawrence Berkeley National Laboratory and Schlumberger.

- Acoustic emissions and microseismicity (AE/MS): A specific R&D topic for microseismic monitoring is increasing the accuracy of locating microseismic events through use of shear wave analysis and use of major events (with high energy output) to locate smaller events (relative positioning).

- Strain monitoring using extensometers and tell-tales: R&D targets include improving rockbolt *in situ* integrity testing in coal, developing a web server platform for remote-reading tell-tale systems, developing civil engineering-oriented remote-reading extensometers.

- Stress monitoring: Stress monitoring R&D includes improvements in the coupling of multiple point extensometers with the host rock.

- Laser scanning: Current research areas include new methodologies for managing the large amounts of data which are generated through accurate 3D laser scanning.

- Satellite imagery: R&D on the application of satellite imagery identified during the workshop included application of hyperspectral imaging and improving the simplicity of SAR interpretation algorithms.

- Radar interferometry: The following limitations of PSI were noted at the workshop and are targets for ongoing R&D:

    - A large SAR data archive is required (a minimum of 30 images) for PSI interferometry. Improvements in algorithms may reduce this number.

- At present, there is no control over scatterer locations.
- PSI is only suitable for line-of-sight measurement; this is not an issue for subsidence or landslide monitoring, but may be for monitoring of tectonics.
- Satellite orbits (and the number of satellites in orbit) limit the current sampling interval to 35 days; the sampling interval is being reduced rapidly.
- The absolute positional accuracy of PSI is not better than 50 m without ground control points (GCPs); relative positional accuracy is better than 1 m.

5.3.2 R&D on Monitoring Technologies in the MoDeRn Project

Specific research and technical development of monitoring technologies is planned in Work Package 2 of the MoDeRn Project:

- Development of magneto-inductive wireless data transmission techniques with the capability of through-the-earth transmission of monitoring data.
- Improvements to the interpretation algorithms used for interpretation of cross-hole seismic tomography data.
- Development of fibre optic sensors for distributed temperature sensing and for monitoring of cement-based materials.
- Development of high-frequency wireless monitoring sensor networks and wireless data transmission using high-frequency signals.

Under Work Package 3 of the MoDeRn Project, demonstration and development of wireless and non-intrusive monitoring techniques will be applied to large-scale experiments in URLs. The *in situ* conditions will reflect typical repository conditions and allow aspects of engineered mock-ups of disposal system components to be monitored.

The following demonstrations will be run:

- In the ***Grimsel Testing and Evaluation of Monitoring Systems (TEM)*** experiment, seismic tomography will be used to monitor resaturation and pressurisation of bentonite. Active cross-hole and hole-to-tunnel seismic methods will be investigated as a means to monitor induced changes to specially constructed features within an underground test facility.

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

Therefore, the objective of the TEM demonstrator is to demonstrate the feasibility and to develop an effective strategy to employ full-waveform inversion as a monitoring tool in the closure stage of an individual disposal cell.

- ***ZigBee*** monitoring technology will be applied in the Grimsel Test Site (GTS) URL. This activity is aimed at demonstrating the potential of using wireless sensor and transmission networks underground, part of which would be immersed in solid material (buffer, concrete, rock, etc), and to manage corresponding energy needs for inaccessible immersed network sensors (nodes). This represents an important first step to verify whether recent advances in using wireless networks to monitor surface-based industry may eventually be transferred to subsurface environments. If technical feasibility can be demonstrated, future studies may then focus on the potential of using wireless networks for specific safety relevant parameters.

- Microseismic measurements and fibre optic sensors will be applied to the monitoring of the ***PRACLAY large-scale heating experiment*** in the HADES URL in Belgium, and wireless monitoring systems will be tested at the HADES URL. The demonstrator will focus on three instrumentation aspects related to the geologically-specific conditions:

    - Fibre-optic based sensing techniques; in particular (1) distributed sensing for minimal cable-feed through, (2) long-term reliability in harsh conditions, (3) extensometry.

    - Micro-seismic characterisation/monitoring; in particular the potential to improve the treatment of signals to gain an understanding of (1) the evolution around the gallery due to excavation/lining and heating and (2) imaging of a water-bearing concretion layer.

    - Wireless data transmission techniques from the HADES URL to the surface; in particular (1) proof-of-principle for magneto-inductive data transmission and verification of the used models, (2) optimizing of energy usage and (3) demonstration of bidirectional data transmission.

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

    The main goal for the monitoring demonstrator is to demonstrate:

    - The capacity to conduct integrated monitoring activities inside the disposal cell, on the cell liner and in the cell near-field;

    - That the designed liner monitoring system is able to withstand construction procedures and to allow for reliable liner monitoring after construction.

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

Information gathered during the Troyes Monitoring Technologies Workshop will inform the further development of monitoring technologies in the MoDeRn Project and the conduct of the research described above.

A key issue for waste management organisation-led monitoring R&D is establishing the long-term stability and reliability of sensors under repository conditions.

6. Summary

The Troyes Monitoring Technologies Workshop brought together 55 experts in the fields of monitoring technologies and radioactive waste management. Discussions at the workshop were facilitated through several means:

- Discussions on specific monitoring technologies at the end of each oral session.
- Extended poster sessions.
- A round-table discussion that was held at the end of the workshop.

The workshop helped to develop ideas on monitoring technology R&D of relevance to monitoring of geological repositories, and contacts were established between a large number of institutions with an interest in monitoring.

The workshop discussed many of the technologies that will be considered for monitoring of geological repositories, including wireless data transmission, fibre optic sensors, geophysical techniques, monitoring of groundwater and chemistry, geotechnical monitoring, and air-based and satellite-based monitoring.

The discussion of the state-of-the-art in these monitoring technologies provides a useful platform for the MoDeRn project partners to use during the remainder of the project. Several R&D projects with a monitoring component were identified and discussed.

Repository monitoring programmes must be based on the specific context under which they are undertaken, and it was recommended that value would be provided to waste management organisations if generic approaches to monitoring, e.g. the MoDeRn Monitoring Workflow shown in Figure 1.1, were developed as part of the MoDeRn Project.

The Troyes Monitoring Technologies Workshop was successful in bringing together monitoring experts from different disciplines and in identification of the state-of-the-art in monitoring technologies.

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8. Appendix A: Workshop Participants and Affiliations

Name	Organisation
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Glauco Feltrin	Swiss Federal Labs for Materials Research and Testing (EMPA) Switzerland
Bernd Frieg	NAGRA, Switzerland
Liz Harvey	Galson Sciences Limited, UK
José Luis Garcia-Sineriz	AITEMIN, Spain
Rainer Glötzl	Glötzl, Germany
Wolfgang Habel	BAM Federal Institute for Materials Research and Testing, Berlin
Jean-Marie Henault	EDF, France
Katerina Krebber	BAM Federal Institute for Materials Research and Testing, Berlin
Michael Jobmann	DBE TEC, Germany
Jere Lahdenpera	POSIVA, Finland
Vincent Lamour	Cementys, France

Name	Organisation
Sylvie Lesoille	Andra, France
Martina Liguanova	RAWRA, Czech Republic
Stefano Marelli	ETH Zurich, Switzerland
Jonathan Marsh	Golder Associates, UK
Stefan Mayer	ANDRA, France
Juan-Carlos Mayor	ENRESA, Spain
Hansruedi Maurer	ETH Zurich, Switzerland
Jitka Miksova	RAWRA, Czech Republic
Ronan Morice	Laborataiṙé National de Métrologie et d'essais, France
Jenny Morris	Galson Sciences Limited, UK
Peter Morris	Salamander, UK
Samira Ouchhi	ANDRA, France
Jaroslav Pacovsky	Czech Technical University of Prague
Andy Parkes	Nuclear Decommissioning Authority, UK
Stuart Pryce	Golder Associates, UK
Philippe Renaud-Goud	UTT, France
Juan Reyes-Mentes	Applied Seismology Consultants, UK
Joachim Schneider-Glötzl	Glötzl, Germany
Thomas Schröder	NRG, the Netherlands
Knut Seidel	GGL Geophysik und Geotechnik Leipzig GmbH, Germany
Assen Simeonov	SKB, Sweden
Peter Simmons	University of East Anglia, UK
Pierre Stephan	EDF, France
Roman Spanek	Technical University of Liberec, Czech Republic
Yasuhiro Suyama	Radioactive Waste Management and Funding Centre, Japan

Name	Organisation
Jiri Svoboda	Centre of Experimental Geotechnics, Prague
Vincent Vanderweijer	TNO, Geological Survey of the Netherlands
Jan Verstricht	EURIDICE, Belgium
Matthew White	Galson Sciences Limited, UK
Gareth Williams	British Geological Survey, UK
Simon Wisbey	Nuclear Decommissioning Authority, UK
Erik Wolfart	Joint Research Centre (JRC), European Commission

9. Appendix B: Workshop Programme

Time	Agenda Item	Presenter	Abstract Number
Day One: Monday 8 June 2010			
1400-1420	Welcome and Introduction	Brendan Breen (NDA)	-
1420-1615	*Oral Session 1: Overview of Applications and Technologies*	*Chair: Brendan Breen (NDA)*	
1420-1445	Introduction to the MoDeRn Project and Repository Monitoring	Stefan Mayer (Andra)	-
1445-1510	Geotechnical Monitoring for Mine Safety and Design	David Bigby (Golder Associates Ltd)	OP.1
1510-1535	Radioactive waste store monitoring	Simon Wisbey (NDA)	OP.2
1535-1600	Civil Structural Monitoring	Wolfgang Habel (BAM)	OP.3
1600-1615	Discussion Session		
1630-1730	*Oral Session 2: Geotechnical and Hydrogeological Monitoring*	*Chair: Michael Jobmann (DBE TEC)*	
1630-1650	The Westbay System – A Platform for Deployment of Sensors for the Hydrogeological Characterisation and Monitoring of Geological Repositories	Bill Black (Schlumberger)	OP.4
1650-1710	The Main Stress Measuring Technique as a More Sensitive Displacement Measurement	Rainer Glötzl (Glötzl GmbH)	OP.5
1710-1730	Discussion Session		
1730-1845	*Poster Sessions 1&2: Overview of Applications and Technologies & Geotechnical and Hydrogeological Monitoring*		
	MoDeRn Project Outline	Matt White (Galson Science Ltd)	PP.1

Time	Agenda Item	Presenter	Abstract Number
	Intelligent monitoring of concrete structures in their environment: ConcreteLife Method	Vincent Lamour (Cementys)	PP.2
	Monitoring Underground CO_2 Storage	Vincent Vandeweijer (TNO)	PP.3
	Multi-packer Systems for long-term hydraulic monitoring at the Bátaapáti Repository, Hungary	Jonathan Marsh (Golder Associates Ltd)	PP.4
	Experimental Closure of the Richard Repository chambers – Short-term Geotechnical Monitoring of the Backfilling Process	Martina Ligaunova (Rawra)	PP.5
	Technical Menu System on Monitoring of Geological Disposal; a Development Report	Jiro Eto (RWMC)	PP.6
	Andra R&D Related to the Monitoring of a Reversible Geological Disposal of Radioactive Waste	Stéphane Buschaert, S. Lesoille, J. Bertrand, M. de Combarieu, J.P. Dubois (Andra)	PP.7
	Contribution of Metrology to the Monitoring of Geological Repositories	Ronan Morice (LNE)	PP.8
	Automated Data Acquisition in Granite	Roman Sparek (University of Liberec)	PP.9
	End User Lifecycle Management Flowchart	Jean-Marie Hénault (EDF)	PP.10
	Biosensing for Groundwater Radionuclides: Uranyl-238 and Surface Layer Proteins	David Conroy (University of Leeds)	PP.11

Time	**Agenda Item**	**Presenter**	**Abstract Number**
Day Two: Tuesday 9 June 2010			
0900-0915	Introduction to Day 2	Brendan Breen (NDA)	
0915-1040	*Oral Session 3: Wireless Sensor Networks and Fibre Optic Sensors*	*Chair: Jose-Louis Garcia Siñeriz (Aitemin)*	
0920-0950	Data Intensive Long-term Monitoring with Wireless Sensor Networks	Glauco Feltrin (EMPA)	OP.6
0950-1020	Distributed Fibre Optic Sensors Embedded in Technical Textiles for Monitoring of Geotechnical and Masonry Structures	Katerina Krebber (BAM)	OP.7
1020-1040	Discussion Session		
1040-1125	*Poster Session 3: Sensor Networks and Fibre Optic Sensors*		
	Extensive Environmental Monitoring of Ground Gases/Vapours	Peter Morris (Salamander)	PP.12
	Fibre Optic Sensors at PRACLAY	Jan Verstricht (Euridice)	PP.13
	SOTA of Wireless Sensor & Transmission Networks	Jose-Louis Garcia-Siñeriz (Aitemin)	PP.14
	Integrated Optical Sensor Networks: Miniaturized Sensors for a Wide Range of Applications	Philippe Renaud-Goud, S. Blaize, G. Leblond, A. Bruyant, P. Royer (UTT)	PP.15
	Sensor Technologies for Packages, Storage and Geological Disposal of Radioactive Waste	Werner Daum (BAM)	PP.16
	Some Examples of the Application of Monitoring Techniques and Sensors to Radioactive Waste Stores	Jenny Morris, S.M. Wickham, T.W. Hicks and P.J. Richardson (Galson Sciences Ltd)	PP.17
	In situ monitoring at the Josef Underground Facility	Svoboda Pacovsky (CTU in Prague)	PP.18

Time	Agenda Item	Presenter	Abstract Number
1125-1230	*Oral Session 4: Air and Satellite Monitoring Technology*	*Chair: Brendan Breen (NDA)*	
1130-1150	JRC Technologies for NPT Monitoring	Erik Wolfart (JRC)	OP.8
1150-1210	Applications of Satellite Radar Interferometry for Terrain-motion Detection and Monitoring in the Nuclear Industry	Ren Capes (Fugro NPA Ltd.)	OP.9
1210-1230	Discussion Session		
1345-1510	*Oral Session 5: Non-intrusive monitoring and wireless transmission*	*Chair: Hansruedi Maurer (ETH Zurich)*	
1350-1410	Sub-surface Interferometry	Andrew Curtis (University of Edinburgh)	OP.10
1410-1430	Quantitative Monitoring of the CO_2 Injection Plume for Carbon Capture	Gareth Williams (BGS)	OP.11
1430-1450	Micro-seismic Monitoring of the Engineered Environment: Developing the Technology across Disciplines	Juan Reyes-Mentes (Applied Seismology Ltd.)	OP.12
1450-1510	Discussion Session		
1510-1600	*Poster Session 4&5: Air and Satellite Based Techniques, Non-intrusive Monitoring, Wireless Transmission*		
	Wireless Transmission Monitoring for Geological Disposal	Yashiro Suyama, J. Eto, K. Yoshimura, H. Tanabe and H. Takamura (RWMC)	PP.19
	Wireless Data Transmission Technology from Repository to Surface	Thomas Schröder (NRG)	PP.20
	Development of Non-intrusive Monitoring using Cross-hole Seismic Tomography	Stefano Marelli (ETH Zurich)	PP.21

Time	Agenda Item	Presenter	Abstract Number
	Latest Technologies for Microseismic, Acoustic Emission and Ultrasonic Monitoring in Radioactive Waste Disposal Feasibility Studies	Juan Reyes-Mentes (Applied Seismology Consultants)	PP.22
1600-1715	*Plenary Session: Key Workshop Topics*	*Chair: Brendan Breen (NDA)*	
1715-1730	*Wrap-up and Conclusions*	*Stefan Mayer (Andra)*	

10. Appendix C: EC Projects with a Monitoring Component

This appendix provides a list of EC projects with a monitoring component, and which were mentioned at the Troyes Monitoring Technologies Workshop.

- ESDRED: Engineering Studies and Demonstration of Repository Designs. http://www.esdred.info/
- FIDES: Optical Fibres for New Challenges Facing the Information Society www.cost299.org
- I-SSB: The Integrated Safe and Smart Built Concept. http://www.issb-project.com/
- LIMES: Land and Sea Monitoring for European Security. http://www.fp6-limes.eu/
- OFSESA: Novel and Reliable Optical Fibre Sensor Systems for Future Security and Safety Applications http://www.cost.esf.org/domains_actions/ict/Actions/ofsesa
- OMNIBUS: Development of the Tools and Interpretation Techniques for Ultrasonic Surveys to Monitor the Rock Barrier around Radioactive Waste Packages in Geological Repositories. ftp://ftp.cordis.europa.eu/pub/fp5-euratom/docs/projrep-omnibus_en.pdf
- POLYTECT: Polyfunctional Technical Textiles against Natural Hazards. http://www.polytect.net/
- RAINOW: Researching the Applications of Open Innovative Wireless Technologies. http://mrsl-research.com/rainow/index.html
- Sustainable Bridges: Assessment for Future Traffic Demands and Longer Lives. www.sustainablebridges.net
- TIMODAZ: Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks. http://www.timodaz.eu/

11. Appendix D: Oral Presentation Abstracts

OP.1: Geotechnical Monitoring for Mine Safety and Design

Dave Bigby, Golder Associates Ltd, UK

An extensive suite of geotechnical instrumentation has been developed over recent years specifically for monitoring mine tunnel and pillar stability. Much of this is manufactured by Golder at their Bretby office (formerly RMT Ltd). Systematic application and monitoring of this instrumentation is essential for maintaining safe working conditions, particularly for rockbolted tunnels in soft rock at depth such as those found in the British deep mined coal industry.

The instrumentation ranges from very simple mechanical devices (dual height rock bolting telltales), which are used to provide a direct visual indication of roof movement for underground personnel, to strain gauged rock bolts and sonic extensometers, which supply very accurate information on the performance of the support system feeding into the observational design process. The information gained from both safety and design monitoring, when combined with stress measurement and monitoring data, generally derived from CSIRO HI cells, is essential for verification of our geotechnical numerical models.

In addition to the instruments mentioned above, the presentation will describe:

- A remote reading telltale and extensometer system which is increasingly being applied around the world in mines and underground caverns. This utilises a contactless transponder suited for wireless adaptation.
- The “Acoustic Energy Meter” which is used for detecting loose rock and voids behind tunnels linings.
- Methods for assessing the in situ integrity of fully encapsulated rockbolts and cable bolts.
- The support management systems which must be implemented to ensure that appropriate trigger action levels are set and responded to.
- The many constraints which apply to mining geotechnical instrumentation such as the potential presence of an explosive atmosphere and the need for rapid installation and low cost.

The presentation will conclude by describing Golder’s current target areas for further Research and Development in the field of mining geotechnical instrumentation.

OP.2: Radioactive Waste Store Monitoring

Simon Wisbey, Nuclear Decommissioning Authority, UK

The Nuclear Decommissioning Authority (NDA) was established in 2005 to effect the clean up of the UK nuclear legacy. It is responsible for 20 former UKAEA and BNFL sites, and is developing geological disposal concepts for all higher activity wastes. Ultimately these will be implemented through a Geological Disposal Facility (GDF).

There is a very large inventory of radioactive material in the UK, which needs to be safely managed in the long term. The conditioning and packaging of raw wastes into disposal containers started in 1990, and these wastes are currently held in more than 10 engineered stores, awaiting the availability of the GDF. It is important to protect the investment in stores and waste packages by adequately controlling the store environment and by monitoring the waste packages for signs of degradation.

In order to ensure application of best practice with respect to the interim storage of packaged wastes, the NDA has initiated an Integrated Project Team (IPT). The key goals of the IPT are to establish a ‘robust’ approach, identify good practice ‘toolkits’, and to publish industry guidance for application in the UK. The IPT is addressing key issues such as waste package performance, store longevity, monitoring and inspection regimes, and store maintenance and refurbishment.

This paper describes the on-going work of the IPT with respect to the following topics:

- Quantifying package performance, focusing on potential outcomes and the definition of package ‘failure’.
- Development of technologies for application in potentially challenging store environments.
- Package re-working techniques.

Examples will be given of current thinking and on-going developments. As the work of the IPT is scheduled to complete in March 2011, the examples presented here are at various stages of evolution, and some remain ‘work in progress’.

OP.3: Civil Structural Monitoring

Wolfgang Habel, BAM, Germany

Civil infrastructure as well as geotechnical and engineering structures come into an age where their integrity and load bearing capacity must be evaluated. New high-performance structures need intrinsic monitoring systems. More often than in the last decades, monitoring systems are used to detect irregularities in the structure's behaviour or damage which influence the safety of the structure. There is a worldwide acting International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII, http://www.ishmii.org) where the key players in civil structural monitoring discus new methodologies, innovations and results.

The presentation at the Andra meeting in Troyes/France introduced the ISHMII and highlighted the most important objectives of civil structural monitoring. It showed examples with a number of different sensor types attached to provide data from historical structure as well as from very slender and innovative structures. Several specially developed fibre optic sensors have been presented to evaluate the integrity and the load carrying capacity of bridges, walls, foundations, columns as well as the stability of heavy rock anchors. A new method for the measurement of the pH value of concrete to indentify corrosion-initiating conditions has been presented, too.

In order to ensure long-term stable measurements with increasingly used fibre optic sensor types, first guidelines and standards for their characterization and validation have been presented. A newly developed facility for evaluation and validation of surface-attached sensors based on fibre Bragg gratings has been explained; its use was strongly recommended to get long-term reliable measurement results with the aim to make trustworthy decisions when damage are detected.

OP.4: **The Westbay System – a Platform for Deployment of Sensors for the Hydrogeologic Characterization and Monitoring of Geologic Repositories.**

William Black, Schlumberger Water Services, Canada

Characterizing and monitoring hydrogeologic conditions at sites proposed for radioactive waste repositories presents a special challenge, in part due to the depth of investigation (deeper than most routine groundwater work), the low-permeability environments that are of most interest, and the demand for quality assurance. Since its introduction in 1978, the Westbay System has become recognized as the leading technology for monitoring and testing groundwater conditions at multiple levels in a single borehole. This presentation will discuss current understandings of the value of detailed vertical profiles of piezometric level and some of the challenges of obtaining good in situ measurements, followed by a description of how the Westbay System approaches these challenges. The presentation will conclude with a history of the Westbay System with respect to geologic repository programs and an update on recent developments involving the system.

OP.5: The Main Stress Measuring Technique As A More Sensitive Displacement Measurement

Rainer Glötzl, Glötzl GmbH, Germany

The author likes to explain the importance but also the difficulties in measuring main stress 3-dimensional and its changes in value as also in the main direction.

With help of very different examples investigated in a salt mine cavern system and in a brown coal mine, we are able to compare and correlate main stress results with deformation measurements.

A highlight will be the main stress measurement and its changes indicating the excavation front already in a distance of 95 m.

A really very new experience approving the headline expression.

OP.6: Data intensive long-term monitoring with wireless sensor networks

Glauco Feltrin, Swiss Federal Laboratories for Materials Testing and Research, Switzerland

In the last decade, wireless sensor networks (WSN) have emerged as a promising technology in the field of structural monitoring. Compared to wired conventional monitoring technologies, the main advantages of wireless sensor networks are fast deployment, little interference and self-organization. Wire removal, however, introduces a serious drawback: Since the nodes have to be operated with batteries, the power supply is very limited. Power saving is therefore of outmost importance in designing, implementing and operating WSN based monitoring systems for medium and long term monitoring.

In WSNs energy consumption is reduced by applying ultra low power hardware and by keeping the sensor nodes in switched-off state for a significant amount of time (low duty cycle). Since communication is the most energy consuming task and the consumption increases exponentially with the transmission distance, power is saved by operating WSNs as multi-hop networks. By establishing communication links only to neighbour nodes, the data are sent to the data sink through several nodes thus reducing the transmission distance.

In data intensive monitoring, however, even a multi-hop network that is operated with a low duty cycle usually achieves a lifetime of only a few days, if, like traditional monitoring systems, all the raw data is transmitted to the data sink. Since in-node data processing is much less energy expensive than data transmission, additional power can be saved by processing the raw data with the goal to reduce the amount of data for transmission (sending of information instead of raw data). When monitoring vibration based processes, which produce large samples of raw data, this strategy is the most powerful energy saving method.

Adopting the described power saving methods, however, has several drawbacks. Low power hardware severely limits the computational resources (typically a micro-processor with a few MHz and kB of memory) and the data acquisition quality (typically 12 bit resolution). Multi-hop and low duty cycle operation limits the communication bandwidth and requires a high level of temporal and operational coordination between the nodes. In-node data processing requires an efficient implementation in terms of speed and memory and, since it is time consuming, a perfect coordination with all other tasks (time synchronization, routing, etc.).

Long-term field operation tests are fundamental to assess the performance of data intensive monitoring with WSNs. Firstly, system stability (hardware and software) and availability is very important and can only be proven with time. Secondly, long seasonality period and continuously changing weather conditions make it difficult to apply indoor system test results to predict outdoor system performance. Finally, varying weather conditions and electromagnetic interference might degrade the quality of wireless communication links and data acquisition.

These issues have been investigated with a long-term test on a cable-stayed bridge. The goal of this deployment was to monitor the tension force of cable-stays via natural frequency estimations that are computed from low amplitude ambient vibration measurements. The monitoring system consists of 6 sensor nodes that are mounted on 6 cables and the root node (data sink) that is located under the bridge deck. An additional node operates as a relay node to improve the communication link between the nodes mounted on the cables and the root node.

Three years of field test experience demonstrated that operating a wireless networks reliably over a period of months or years was a challenging task. Most problems relied on balancing the requirements of a data intensive application with the requirements of minimizing power consumption for a achieving a sufficiently long battery lifetime. The problems could be solved with several hard- or software improvements. The network operates now absolutely stable and without any maintenance activity over several months. Its availability could be improved from the initial 60% to 98% and its lifetime could be extended to more than 6 months. Despite the severe hard- and software limitations, the generated information complies with the quality requirements in civil engineering. The results obtained by this investigation demonstrate that there are no fundamental obstacles which prevent the application of long term monitoring systems based on wireless sensor networks. The hardware and power limitations, however, require a tight specialization to the monitoring task.

OP.7: Distributed Fibre Optic Sensors Embedded in Technical Textiles for Monitoring of Geotechnical and Masonry Structures

K. Krebber[1], P. Lenke[1], S. Liehr[1], N. Noether[1], M. Wendt[1], A. Wosniok[1], J. Schneider-Gloetzl[2], R. Gloetzl[3]

[1] BAM Federal Institute for Materials Research and Testing, Berlin, Germany,

[2] Glötzl GmbH, Rheinstetten, Germany, 3RG Research, Ettlingen, Germany

Technical textiles are commonly used within several industrial sectors ranging from earthworks, construction, civil engineering and transport, to name a few. For example, technical textiles are extensively used in construction for reinforcement of earthworks and masonry structures like dikes, dams, railways, embankments, landfills, slopes, masonry walls and buildings. The retrofitting of existing masonry walls and soil structures by technical textiles gains more and more importance especially in connection with earthquake protection of historic buildings and protection of roads and railroads embankments against landslides.

The incorporation of optical fibres in technical textiles leads to additional functionalities of the textiles, e.g. monitoring of mechanical deformation, strain, temperature, humidity, pore pressure, detection of chemicals and ionizing radiation, measurement of the structural integrity and health of geotechnical and masonry structures (structural health monitoring). Thus, “smart” technical textiles can be realized. Especially solutions for distributed measurement of mechanical deformation (strain) over extended geotechnical areas of some hundred meters up to some kilometres are urgently needed. Textile-integrated distributed fibre optic sensors can provide for any position of extended geotechnical structures information about critical soil displacement or slope slides via distributed strain measurement along the fibre with a high spatial resolution of less than 1 m. So an early detection of failures and damages in geotechnical structures of high risk potential can be ensured. Especially the integration of polymer optical fibres (POF) in technical textiles is very attractive because of the high elasticity, high breakdown strain and the capability of POF of measuring strain of more than 40 %.

Europe has driven substantial developments in smart technical textiles technologies. Within several German projects and the European project POLYTECT distributed fibre optic sensors mainly based on Brillouin scattering in silica fibres and OTDR in POF have been developed for the above mentioned monitoring purposes.

The POLYTECT project particularly focuses on the development of polyfunctional technical textiles against natural hazards. The development of both textiles and fibre optic sensors has significantly advanced and a number of field tests have successfully been conducted (see Fig. 1 and Fig. 2). The workshop presentation will highlight five years of research at BAM toward the realization of such multifunctional technical textiles with embedded distributed fibre optics sensors for monitoring geotechnical and masonry structures.

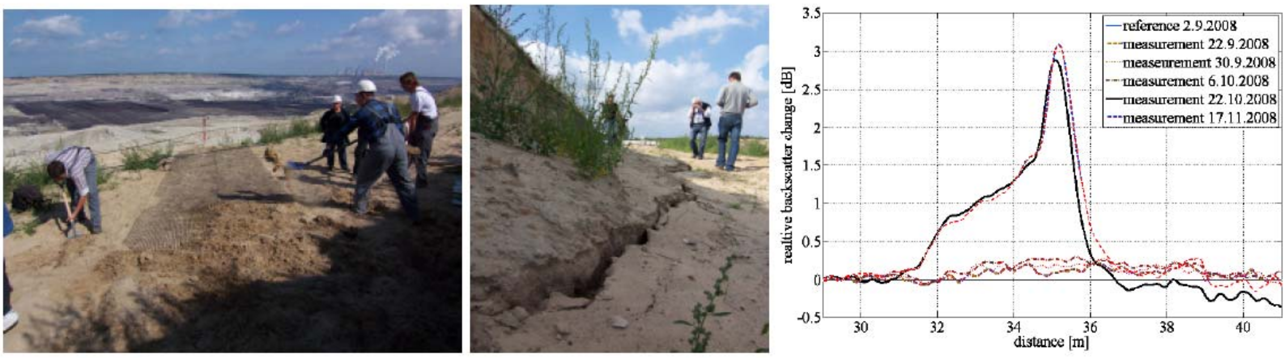


Figure 1: Installation of a geogrid containing POF at a creeping slope in a brown coal pit near Belchatow, Poland (left), cleft in the slope (middle) and monitoring of the cleft and the increase of the cleft by a distributed POF OTDR sensor (right).

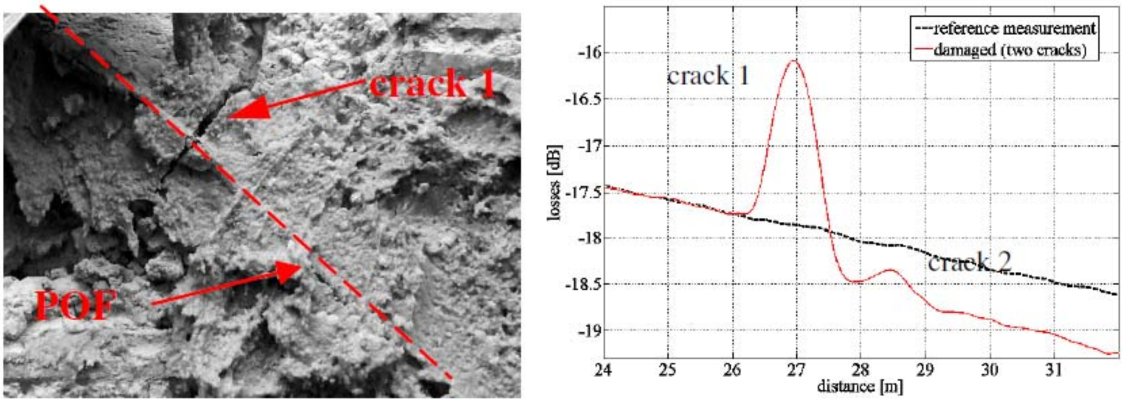


Figure 2: Masonry structure with an embedded POF (left) and detection of two cracks in the structure by a distributed POF OTDR sensor (right).

OP.8: JRC Technologies for NPT Monitoring

Erik Wolfart[1], Gunnar Boström[1], João G.M. Gonçalves[1], Olli Okko[2], Vítor Sequeira[1]

[1] European Commission - Joint Research Centre, Ispra, Italy

[2] STUK - Radiation and Nuclear Safety Authority, Helsinki, Finland

The talk will present two technologies developed at the European Commission's Research Centre (JRC) for use in nuclear safeguards: Firstly, an integrated information platform targeted at the image analyst in the context of satellite-based NPT monitoring, which has been developed in the frame of the LIMES research project. Secondly, laser-based 3D Reconstruction and Verification technologies, which have been used to create an accurate, as-built 3D model of the Finish geological repository, known as Onkalo.

Integrated Information Analysis for NPT Monitoring

Nuclear safeguards has always been information driven. However, in recent years the volume and variety of information has continuously been increasing, for instance through the implementation of the Additional Protocol, increased use of novel technologies and availability of Open Source information. Therefore, an integrated, all-source information analysis is paramount for an efficient and effective monitoring of the Non-Proliferation Treaty (NPT).

LIMES - a FP6-funded project developing satellite-based services for a range of security-related applications - addressed this problem with an integrated platform supporting the non-proliferation image analyst in verifying treaty compliance. The main benefits of the platform are:

- integrating information from multiple sources and time-frames, including satellite imagery, site models, open source information, reports, etc.
- improved information management using a GIS-based platform.
- enhanced methodologies for satellite image analysis, e.g. in the areas of object-based change analysis, 3D information extraction and processing of radar imagery.

LIMES carried out two service demonstrations in 2008 and 2009. The test site was the nuclear power plant Olkiluoto, where Finland is constructing a new nuclear reactor and a geological repository, which is called Onkalo at the present stage. The demonstration scenario was to monitor the reactor construction using different types of satellite imagery as well as Open Source information.

Laser Scanning at Onkalo Facility

Within the framework of a collaboration between the JRC and STUK, Finland Radiation and Nuclear Safety Authority, it was decided to make a field trial of JRC's 3D Reconstruction and Verification laser technologies to accurately model the Onkalo tunnel. The exercise aimed at sharing information and practices concerning measurement equipment and methodologies including data processing and visualisation software. The 3D model documentation provides an accurate 3D verification of the underground facility. The documentation can be relevant to detect future changes indicating the presence of undeclared rock spaces. The exercise showed that (a) 3D laser technologies can be easily deployed to create accurate models of sites "as-is" and (b) it is possible to perform design verification of large underground facilities.

OP.9: **Applications of Satellite Radar Interferometry for Terrain-Motion Detection and Monitoring in the Nuclear Industry**

Ren Capes, Fugro NPA Ltd, UK

Satellite radar interferometry (InSAR) is presented as a unique complement to the surveying practices undertaken by the nuclear industry during sites assessments or ongoing stability-monitoring of existing facilities.

InSAR is a non-invasive surveying technique able to measure millimetre-scale motions of terrain features over wide areas. It does this by comparing the inherent phase data in the echoed signal from individual radar scenes in a multi-temporal data-stack that might span up to 18 years (1992 to present). This enables an unprecedented 'historical' analyses of past motions as well as the capability to provide ongoing monitoring into the future. Typical terrain-motions include subsidence, heave, slides, crustal deformation and structural instability.

Three types of InSAR are presented: Conventional Differential InSAR, Persistent Scatterer InSAR, and Artificial Reflector InSAR, all using examples of relevance to those involved in geological site-assessment or the ongoing monitoring of existing facilities.

The accuracy and precision of InSAR services provided by Fugro NPA Ltd have been fully validated as part of the European Space Agency project *Terrafirma* where precision was confirmed at around 0.5mm per year with an overall accuracy of 1-2mm per year. Via this work, FNPA is now one of only five organisations formerly certified as an InSAR provider working to quantified tolerances and quality control.

OP.10: Sub-surface Interferometry

Andrew Curtis, University of Edinburgh, UK

The field of Seismic Interferometry exploded onto the earthquake and industrial seismological scene within the past seven years. It allows seismic tomography of the Earth's subsurface to be performed using only background vibrational noise (with no identifiable sources of energy), seismometers to be turned into virtual (imagined) sources of energy that produce real seismograms, and I will show that real energy sources (e.g., earthquakes) can be turned into virtual seismometers deep inside the solid Earth (without drilling) - that is, we can use one earthquake as a seismometer to record seismograms from another earthquake.

Our most recent advances have shown how interferometry provides generalised, nonlinear methods to form images of the Earth's interior, and that it embodies completely new Optical Theorems of Physics. Bizarre, but true; and it's very new.

I will provide a clear explanation for a general Geoscience audience of what interferometry is, how it works, and the various advances listed above.

OP.11: **Quantitative Monitoring of the CO_2 Injection Plume for Carbon Capture**

Dr. Gareth Williams, British Geological Survey, UK

CO_2 produced at the Sleipner gas field is being injected into the Utsira Sand, a regional saline aquifer beneath the northern North Sea. Injection started in 1996 with some 11 Mt of CO_2 now injected. Time-lapse seismic surveys have been acquired in 1999, 2001, 2002, 2004, 2006 and 2008 in order to monitor the growth of the plume. The plume is imaged as a sequence of high amplitude sub-horizontal reflectors within the aquifer; the reflections are thought to represent mostly tuned responses from thin layers of CO_2 trapped beneath intra-reservoir mudstone baffles (Figure 1). Time-lapse imaging of the overburden shows no evidence of CO_2 migration from the reservoir.

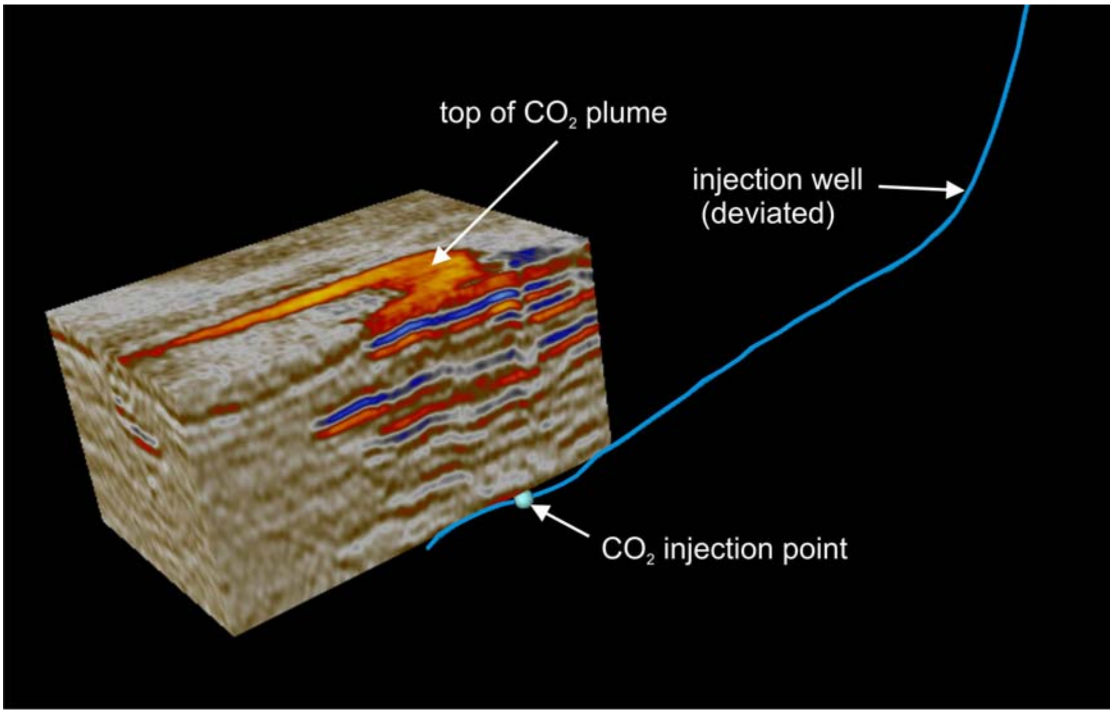


Figure 1: The 2006 time-lapse seismic cube showing the plume and the topmost CO_2 layer

Quantitative interpretation analysing reflection amplitudes and velocity pushdown was able to obtain a satisfactory, though non-unique, mass verification for the 1999 plume, but since then, increasing signal attenuation in the deeper part of the plume have rendered this progressively more difficult.

The topmost layer of the plume is perhaps the most tractable in terms of detailed analysis. It is very clearly imaged, with detectability down to about 1 metre, and does not suffer from the effects of progressive signal attenuation. The manner in which the layer is spreading laterally beneath the reservoir topseal is providing clear insights into how the plume will behave into the future. History-matched flow simulations of the topmost layer indicate lateral migration within a very high permeability (> 3 Darcy) sand, largely controlled by buoyant ponding beneath a rough cap rock topography. Perfect history-matching of the layer spread is challenging however, likely due to small uncertainties in the depth-converted base topseal surface.

Although full quantitative verification of injected mass is not a European regulatory requirement, the regulations do require that robust understanding of current storage behaviour can be demonstrated and that predictions of future performance are reliable. In particular the EU Storage Directive requires the following key criteria to be met for site closure:

- The actual behaviour of the injected CO_2 conforms with the modelled behaviour
- There is no detectable leakage
- The storage site is evolving towards a situation of long-term stability

By combining high quality monitoring datasets such as at Sleipner with long-term predictive simulations and key observations from pilot-scale projects, particularly those in the post-injection phase such as at Nagaoka, it is proposed that storage sites can be closed under the developing (European) regulatory regime.

OP.12: **Microseismic Monitoring of the Engineered Environment: Developing the Technology across Disciplines**

Juan Reyes-Mentes, Applied Seismology Consultants, UK

The passive monitoring of microseismic events induced in rock and rock-like materials subject to stress changes imposed by the engineering of the medium provides a unique means of monitoring the effect of the treatment and the changes imposed on the induced or pre-existing fracture network. Microseismic (MS) monitoring combined with active acoustic surveys is now a established technique used in a wide range of disciplines and scales from hydraulic fracturing and reservoir monitoring in petroleum, enhanced geothermal systems, mining, radioactive waste storage, carbon dioxide storage, engineering and laboratory testing.

In the petroleum and geothermal sectors, microseismic monitoring, also known as “passive seismic”, allows engineers to visualise active fracture networks within developing or producing fields. Real-time processing of microseismic data can provide feed-back of information to engineers on the position, growth and effectiveness of a hydrofracture stimulation, or can map extraction and injection paths in a producing field. Advanced analysis of microseismic data yields information on fracture networks such as distribution, persistence and orientations, and can describe the mechanisms behind the fracture growth leading to a better understanding of the reservoir behaviour.

Microseismic monitoring provides a unique insight into the fractures induced by mining operations. Locating events and determining their source parameters provides information on the zoning of rock damage and the fracturing process. The continuing development of advanced location algorithms allows to minimise uncertainties imposed by a complex velocity structure. Analysing a catalogue of microseismic data provides information on the distribution and geometry of fracture networks and their relationship to mining operations. The advance in computing power has allowed the integration of field microseismic field observations with numerical models to study fundamental modes of rock fracture, in particular, the Particle Flow Code (PFC) is currently used to create and test "synthetic rock" and compare the predicted spatial and temporal trends in fracturing directly with microseismic data obtained in the laboratory or field. This represents a powerful combination of tools that can be applied to the development of predictive models for a wide range of rock mechanics problems.

Analysis of Acoustic Emission (AE) and ultrasonic data allows scientists and engineers to monitor the patterns and mechanics of fracture growth during laboratory testing. High-frequency electronics coupled with real-time data processing software provides cost effective solutions with the high data-flow rates and specifications that can be tailored to reach the resolution required for each scale and application. For example, the recording of entire continuous time series allows to examine the microcracking and deformation processes from acoustic emissions occurring during laboratory rock-fracture experiments. It is then possible to evaluate, dissect, process and interpret this data using continuous waveform and sonogram visualization, and standard scaled seismic techniques.

Geological reservoirs represent an ideal solution for the permanent storage and confinement of hazardous materials and greenhouse gases. In order to assess the feasibility and performance of geological sequestration as a long-term solution for hazardous waste management or CO_2 depletion, it is crucial to evaluate and monitor the integrity and stability of the host rock or engineered structures. Active surveys combined with passive monitoring provide a unique tool to evaluate the evolution of fracturing around the engineered reservoir. Acoustic surveys allow monitoring changes in the rock mass through the inversion of changes in acoustic wave transmission velocity into characteristics of the fracture network. MS monitoring allows to map potential paths for fluid migration allowing to take remediation steps to maintain the integrity of the repository.

12. Appendix E: Poster Presentation Abstracts

PP.1: MoDeRn Project Outline

Matt White[1], Brendan Breen[2] and Stefan Mayer[3]

[1]Galson Sciences Ltd., UK, [2]Nuclear Decommissioning Authority, UK
[3]Andra, France

Early work in the MoDeRn Project has included preliminary development of a generic structured approach – the MoDeRn Monitoring Workflow, which provides a methodology for developing and implementing a monitoring programme under specific national boundary conditions (Figure 1). This poster presents the preliminary MoDeRn Monitoring Workflow and illustrates how the workflow relates to work being undertaken in the project (Figure 2).

Development of the MoDeRn Monitoring Workflow will continue throughout the project. The workflow will be tested by the detailed work in each work package task, and will be revised based on the outcomes. It is anticipated that the MoDeRn Monitoring Workflow will provide a reference framework against which specific monitoring programmes can be developed with due consideration of the appropriate boundary conditions (i.e. the national context).

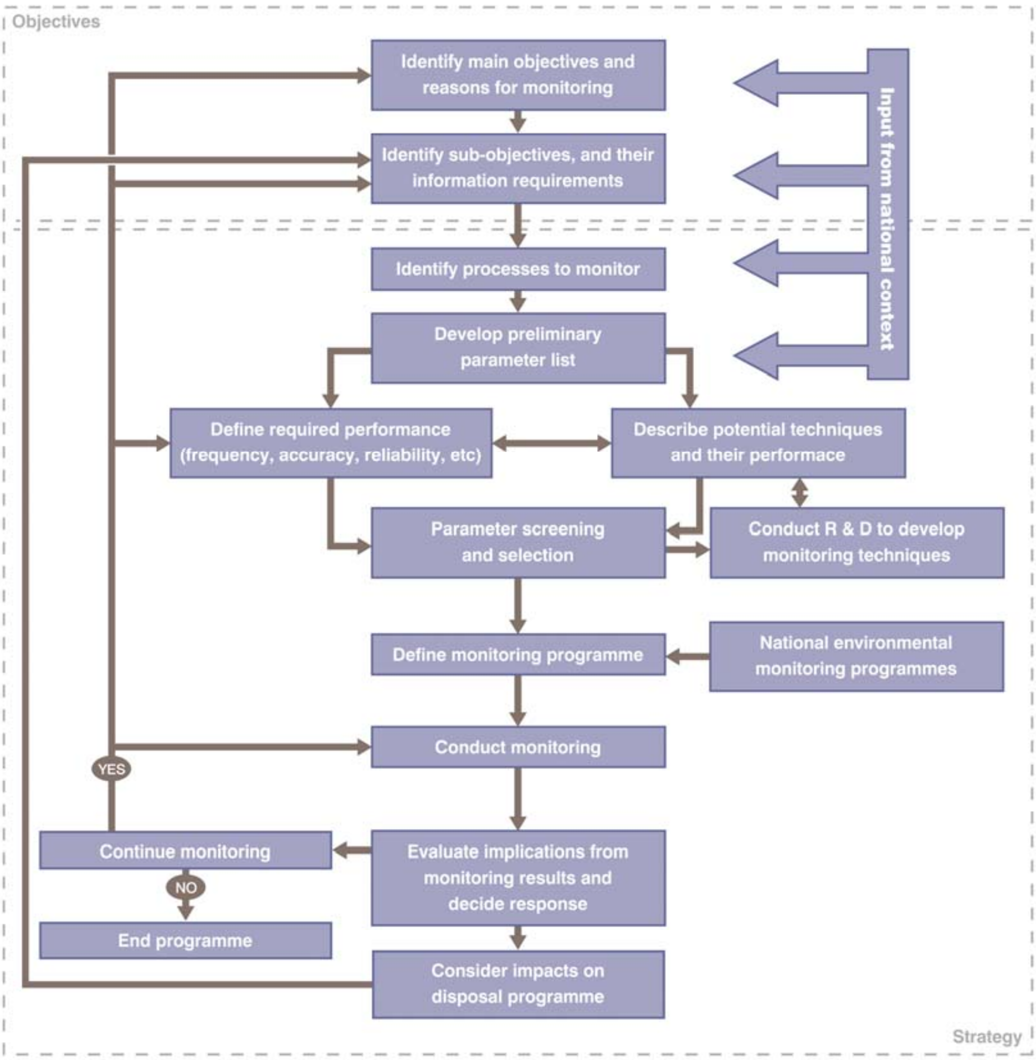


Figure 1: The Preliminary MoDeRn Monitoring Workflow.

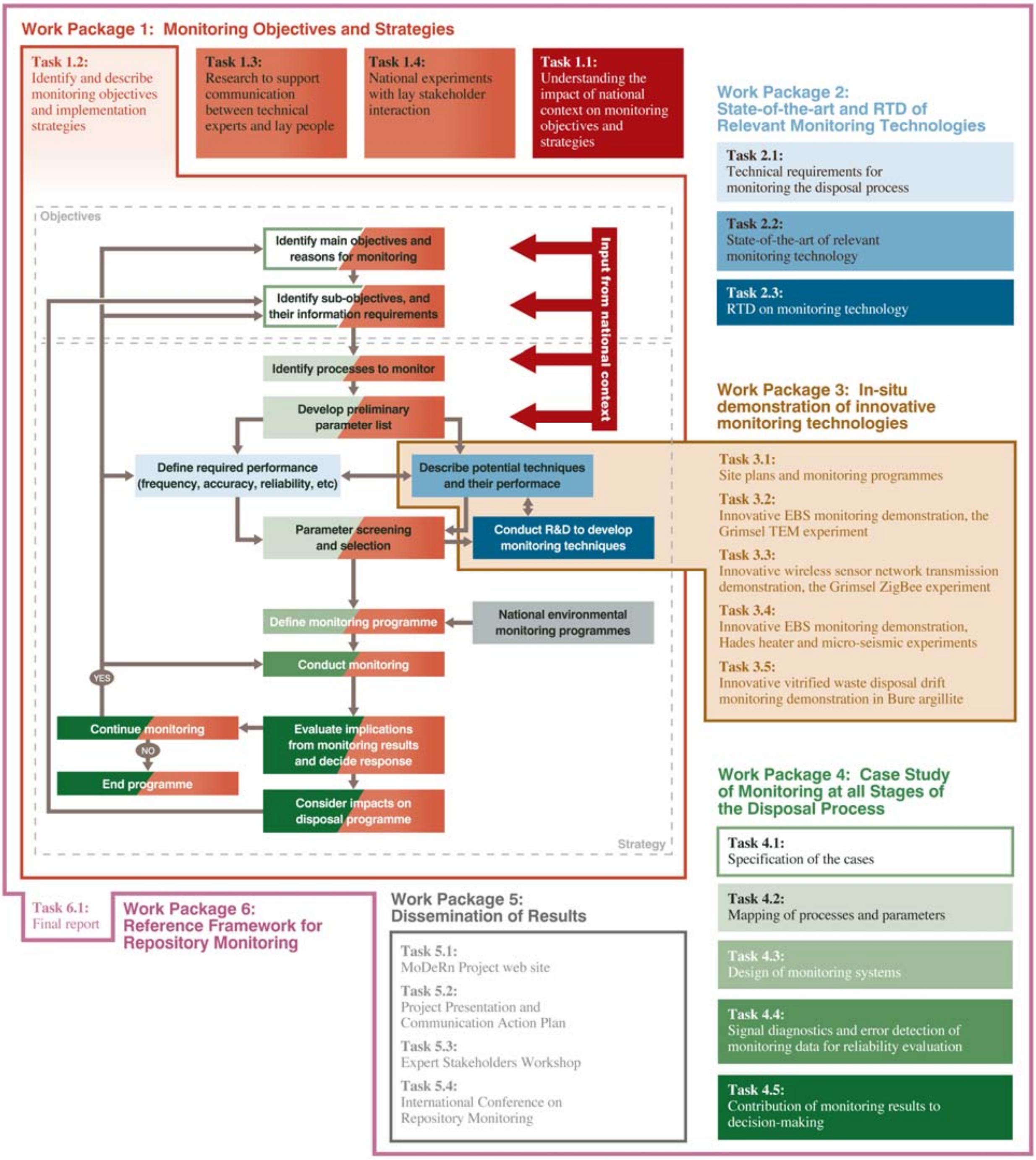


Figure 2: Relationship of the Preliminary MoDeRn Monitoring Workflow to MoDeRn Project work package tasks.

PP.2: **Intelligent monitoring of Concrete Structures in their Environment: *ConcreteLife* Method**

V. Lamour, A. Haouas, V. Lanticq, Cementys, France

The *ConcreteLife* method is based on the report that the measures issued from concrete structures incorporate not only the behaviour of the structure (mechanical loading, hydro-thermal gradients, degradation) but also the behaviour of concrete material (shrinkage, swelling, early age behaviour, pathological damages) and the environment (sunlight, hydro-thermal exchanges, rainfall) (Figure 1). In order to disassociate these three components, this method provides an innovating system based on specific structure/material instrumentation and interpretation schemes. The total and continuous thermo-hydro-mechanical measured strains are thus dissociated depending on their type (free, mechanical, cracking) and origin (thermal, shrinkage, elastic, creep…) by using instrumented witness test samples both independent and bounded to the structure. Finally, we are able to monitor the onset of damage like cracking from the previous calculated mechanical strains evolution basing on defined criteria. In application to this method, we present a long-term experimental data analysis of a basic nuclear installation for solid low- and intermediate-level short-lives radioactive waste. This analysis quantifies the thermal gradient biaxial stresses through the monitored large reinforced concrete structure and their affects on the mechanical behaviour.

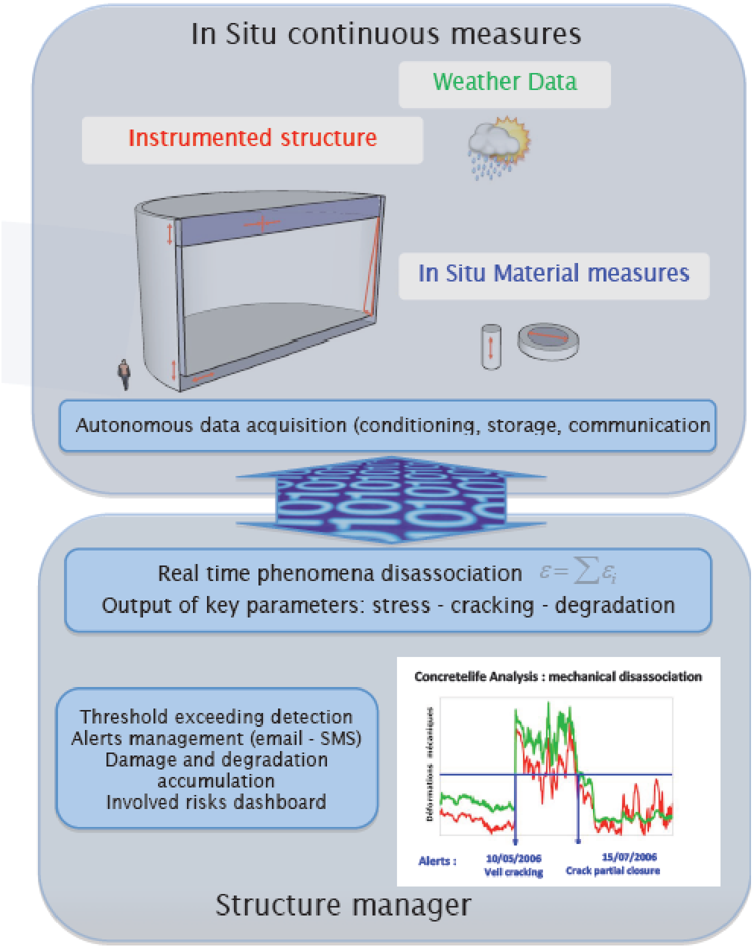


Figure 1: Schematic illustration of the ConcreteLife method.

PP.3: Monitoring Underground CO_2 Storage

Vincent Vanderweijer, Filip Neele and Rob Arts, TNO, the Netherlands

Introduction

Despite the efforts directed at the development of the large scale application of sustainable energy, the world still heavily depends, and in the next decades will depend on fossil fuels. Subsurface storage of CO_2 in geological systems could bridge the transition period required to develop sustainable sources of energy and at the same time reduce the impact of the human activities on climate change.

According to the EU directive on CCS, CO_2 storage will be admitted to the ETS (Emission Trading Scheme) only if monitoring and verification can be carried out satisfactorily. Because of this monitoring and verification are key issues for the implementation of large-scale underground storage of CO_2.

Monitoring

Monitoring serves several important purposes: gathering evidence for the save and secure short and long-term containment of CO_2 and in the case of the detection of unwanted/unplanned migration of CO_2: Warn, so corrective measures can be undertaken.

Monitoring and verification of stored CO_2 can be performed by measuring the absence of any leakage through direct and indirect methods. Verifying indirectly that the CO_2 is behaving as expected in the reservoir would be based on static and dynamic modelling and updates corroborated by monitoring data. In practice, a combination of approaches will often be required and the optimal monitoring plan will be guided by the risk assessment and site characterization.

Quantitative monitoring for the ETS is expected only to be required if there is an indication of leakage. But for this type of monitoring several issues need to be taken into account. These are: the resolution and the accuracy of the individual monitoring methods and the parameters that are measured by the monitoring method and their dependence on quantity or concentration of CO_2. Important aspects are the spatial sampling of the storage site (the location of the measurements) and the temporal sampling (how often measurements are taken). Taking into account all these different aspects, we suggest a model-driven, scenario and risk-based monitoring approach where multiple techniques are used to optimally monitor a CO_2 storage site.

Permanently installed monitoring equipment can effectively contribute to the suite of tools already available. Certainly where cost efficiency comes into play autonomous permanently installed monitoring equipment could effectively reduce costs and still provide accurate updates on storage efficiency.

During this session an overview will be given of a large suite of monitoring tools currently available in combination with their suitability to monitor seal integrity, fault integrity, well integrity, ground movement and/or leakage of saline fluids, Examples will be shown from current CO_2 storage projects.

PP.4: Multi-packer Systems for Long-term Hydraulic Monitoring at the Bátaapáti Repository, Hungary

Jonathan Marsh, Golder Associates, UK

The Bátaapáti site is located in southern Hungary and was selected for geological disposal of low and intermediate level radioactive wastes. Investigation of the site started in 1995 with several deep boreholes and surface geophysics. Excavation of two inclined access tunnels and the underground facility began in 2005 and the first two disposal galleries are planned to put into operation in 2011. In Hungary, the safe management and disposal of radioactive wastes is the responsibility of PURAM (Public Agency for Radioactive Waste Management).

The repository is situated at a depth of ca. 250 m below ground surface, in a hilly area. The host rock of the facility is the Paleozoic Mórágy granite formation. Granitic rocks are relatively densely fractured and have a complicated tectonic structure. The granite covered by Quaternary sediments with a thickness of about 50 m that restricts the utility of surface investigation methods. Therefore, borehole geophysics and hydraulic testing played an exclusively important role in site understanding. According to the present hydrogeological conceptual model, the Bátaapáti site has a strongly compartmented flow system composed of well connected rock blocks, separated by sealing fault zones.

Multi-packer monitoring systems were installed into all of the 300-500 m deep surface boreholes and some of the underground sub-horizontal drill holes. These multi-packer systems were developed by Golder Associates Germany and Hungary in a modular way, using similar equipment to that of the traditional hydraulic packer testing. 4 to 6 Comdrill packers are placed in each hole and pressurised by nitrogen gas or water. Downhole pressure and temperature gauges are connected with each of the monitoring zones and downhole loggers collect and store the data and transport them to the surface read-out system in a digital form. The modular data acquisition system was developed by AquiTronic GmbH, Germany.

The multi-packer systems are relatively simple, easy to install, operate and it is possible to retrieve, rebuild and reuse them. 19 systems are running now in surface boreholes with a total of 106 monitoring zones, and another 10 systems are operating in underground holes and measuring pressure in 48 observation zones. Some of the systems have been working for more than 10 years now without any problems and 97% of the installed zones is still in operation.

The developed multi-packer monitoring systems are reliable and provide high quality data. They helped to refine the hydraulic head profile along the holes. 8 large-scale interference tests were carried out using these systems. Groundwater was pumped from one of the boreholes and pressure response in tens of observation zones were monitored in the sur-rounding boreholes. These tests produced the most valuable information about the hydrogeology of the site and input data for numerical groundwater modelling. Monitoring of the drawdown and transient pressure processes during construction of the repository is a unique and non-repeatable opportunity for mapping the main hydraulic features of the site. Some of the multi-packer systems underground were specially developed for in situ tracer tests and diffusivity experiments, to define transport properties and parameters of the host formation.

PP.5: Experimental Closure of the Richard Repository Chambers: Short-term Geotechnical Monitoring of the Backfilling Process

Martina Ligaunova, Rawra, Prague, Czech Republic

Low-level and intermediate-level waste has been disposed of in the Richard repository since 1964. In 2006 – 2007, experimental closure of three disposal chambers in the Richard repository was realized by technology designed by DBE TECHNOLOGY GmbH.

The main feature of this concept is the implementation of the hydraulic cage around the disposal chambers, consequently filled with waste packages. The system of the hydraulic cage was realized by backfilling waste packages with a special type of low-permeability concrete and building a highly permeable (gravel) layer in a gap between the waste/concrete body and the wall of the chamber. The gravel layer fulfils the role of a preferential pathway for the possibly present groundwater whilst the waste is enclosed in the low-permeable barrier.

Short-term geotechnical monitoring was performed in a stage of backfilling of the waste body in the chambers. The purpose of this monitoring was to continuously measure the parameters necessary for maintaining the quality of the backfill material and for confirming perfect backfill of the all spaces in the chamber. To achieve and maintain requested quality of the concrete used, the hydration heat development was monitored. The system of temperature sensors at selected locations and various height levels in the chambers was installed. Visual control of the continuous backfilling of the chamber was performed by means of a number of simple web cameras installed at suitably chosen positions on the chamber ceiling. The obtained results prove high quality of the chamber closure.

PP.6: Technical Menu System on Monitoring of Geological Disposal, a Development Report

Jiro ETO[1], Yasuhiro SUYAMA[1], Kimitaka YOSHIMURA[1]*, Hiromi TANABE[1] and Takeshi SUGIYAMA[2]

[1]: Radioactive Waste Management Funding and Research Center, Japan

[2]: Japan NUS Co., Ltd., Japan

*: Current affiliation; Nuclear Waste Management Organization of Japan, Japan

Introduction

Radioactive Waste Management Funding and Research Center (RWMC), Japan has carried on researches of monitoring activities on geological disposal such as analyses of expected requirements, technical limitations and regulations, and also has developed key technologies such as wireless monitoring system. A menu system has been developed as a tool to supply technical options for monitoring activities on geological disposal.

Technical Menu System

Supposed users of the system are implementing organizations, regulators and other stakeholders of geological disposal. The system provides a link between users and potential monitoring technologies. The users have various purposes of and requirements for monitoring activities, thus the system has been developed on the basis of space-time relations in staged program for geological disposal.

The system includes information of technical requirements and a list of instrument for monitoring. Users can obtain selected information, using a space-time matrix and following matrix of parameters of monitoring. The space-time matrix is composed of places such as drift or EBS, and project phases such as site-selection phase or construction phase of disposal site. After the selection of a place and a project phase, and a parameter, user can see details of candidate instruments selected from a database mainly composed of c.a. 500 conventional, commercially available equipments.

Next Step

The system is expected to be available for implementing organizations and regulators to consult during the development of site characterization plans, after a trial period to update the system and included information. For the update, a feedback system is also installed.

PP.7: Andra R&D Related to the Monitoring of a Reversible Geological Disposal of Radioactive Waste

S. Buschaert, S. Lesoille, J. Bertrand, M. de Combarieu, JP. Dubois, Andra, France

Monitoring (named "observation et surveillance" in Andra terminology) is an important aspect of the reversible management process of deep geological radioactive waste disposal. Observation and surveillance is considered an approach complementing all design choices made to comply with safety and reversibility requirements of the repository. It relies on a monitoring strategy well adapted to the repository design.

The monitoring strategy and design of monitoring systems aim to provide technical and scientific information and give additional knowledge, all along the management of the disposal. This is not restricted to structural health monitoring of civil engineering (*i.e.* thermo-mechanic monitoring), for which a number of well known and robust approaches are available. It also aims to survey the chemical and hydraulic evolution of materials used in the disposal or the atmosphere of cells and thus covers all the measurement fields: « T-H-M-C » (Thermal – Hydraulic – Mechanic – Chemical). In addition, specific attention is invested in monitoring of elements important to the long term safety of the repository (engineered barriers such as seals, host rock). Finally, monitoring technology must be adapted for use in the environmental conditions of the repository (pressure, humidity, temperature, localized radiation…).

Andra's strategy to develop repository monitoring is based on:

- The inventory and selection of available, reliable and robust technology; and, to cover a broader range of potential monitoring needs and to better adapt technology to specific repository monitoring requirements.
- A comprehensive R&D program launched in 2007-2008 within the framework of a "laboratories group" (for "Groupement de laboratoires": GL) managed by Andra and specialized in instrument development, their metrological qualification, their strengthening, etc. These laboratories are from university or public research institutes or are companies: LAAS-CNRS, LCPC, Inéris, LNE, UTT, EDF R&D, PACT company, University of St Etienne, BRGM, Cémentys company, etc. Some of them present their R&D actions at this Modern workshop on R&D.
- In situ tests in Andra's underground research laboratory of monitoring technologies and monitoring systems designed for use in a future repository.
- The "GL" R&D topics address varied, complementary subjects ranging from miniaturization of sensors to applications in civil engineering environment. The objective is to regularly update the current design of monitoring systems by newly developed instruments. The R&D topics are grouped in three main categories:
    - R&D on sensors allowing an *in situ* instrumentation: Tests in laboratory or in diverse building sites have been started from 2008 for available or prototype "T-H-M" sensors and will generally be followed at least till 2012. R&D on chemical sensors are currently at a more preliminary stage.

- R&D on wireless communication in underground environment in order to estimate the space and time electromagnetic field necessary to identify the optimal position for transceivers (transmitting and/or receiving) units, like a wireless sensor node. These types of sensors, which will be used in a wireless network, will be developed in the way to be redundant, if necessary, to the *in situ* instrumentation.

- R&D on non destructive methods. They present a good potential to satisfy some needs of disposal survey, as evaluation of structural health monitoring or the survey of disposal cell atmosphere and especially give the possibility of an improvement of longevity of the monitoring design.

Examples of main Andra R&D actions will be illustrated in the poster presented during workshop.

PP.8: Contribution of Metrology to the Monitoring of Geological Repositories

Ronan Morice, LNE, Paris, France

Many important decisions are based on measurement. Hence, good-quality results are essential. It is well accepted worldwide that traceability to stated references (e.g. standards of the International System of Units) is an essential condition to a reliable result. However absolute certainty is an unattainable ideal : metrological traceability must therefore be established together with an evaluation of uncertainty. In the field of repository monitoring, the specialist has to give confidence by a clear demonstration that the performance of the measurement process is consistent with the expected requirements. This, at the time of investigation and over the period of exploitation – even over 100 years.

Metrology is the « science of measurement … made at a known level of uncertainty, in any field of human activity ». It provides a technical framework to demonstrate and maintain confidence in the quality of measurement. The two important concepts of « traceability to standards » and « measurement uncertainty evaluation » are essential to address the metrological needs in the field of geological repositories monitoring; for example:

- The observation of very small environmental changes over very long timescales : are these attributable to instrumental instabilities or to a physical phenomenon?
    - Evaluation in laboratory conditions and on-site checks are required to assess metrological performances in terms of stability, influencing factors… of these instruments.
- The periodical replacement of the electronics, considered a consumable at the scale of several decades.
    - Equivalence between different indicators is ensured by a calibration (readings corrected for systematic deviations). Periodical calibration provides also evidences of the performances and history of the instrument.
- The evolution over time of the technical framework (e.g. concepts, definitions, mathematical tools …):
    - Concepts in metrology have been mainly formalized in two written standards internationally accepted: the GUM – Guide for the Expression of Uncertainty in Measurement, and the VIM – International Vocabulary of Metrology. A continuous revision of this technical framework is thus provided by Metrology Organisations.

The poster presented in this workshop proposes to illustrate the possible contribution of metrology to the monitoring of geological repositories.

PP.9: Automated Data Acquisition in Granite

Roman Špánek, University of Liberec, Czech Republic

Various geographical, geophysical and geochemical methods have been applied in the Bedrichov water tunnel (approximately 120 km North from Prague) to characterize the geological environment and the fractured granite host rock.

The Bedrichov water tunnel was excavated in the Jizera Granite, one of the dominant rock types of the Variscan Krkonoše-Jizera composite massif, to accommodate a water pipeline from the Josefùv Dùl water dam to a water treatment plant situated in the Bedrichov mountain village. The 6000 m-long tunnel has a diameter of 2.5 to 3.5 m, and was excavated by tunnel boring machine and destructive mining technologies at a depth of approximately 100-200 m below the ground surface.

The Boito tunnel was investigated as a generic analogue of an underground research laboratory, as part of the Czech Republic nuclear waste disposal program (Klomínský et al. 2005). This has included the instrumentation of the tunnel for automatic data gathering and online access of the following monitoring data:

- Continuous gathering of measured data of springs and water:
  - Water flow.
  - Temperature.
  - pH.
  - Conductivity.
  - Redox.
  - Oxygen.
- Tunnel environment and groundwater:
  - Humidity.
  - Water.
  - Flow rate (Springs & tunnel total inflow).
  - pH.
  - Conductivity.
  - Temperature.
- Rock temperature.
- Continual measurement of rock strain.
- Ground acceleration.

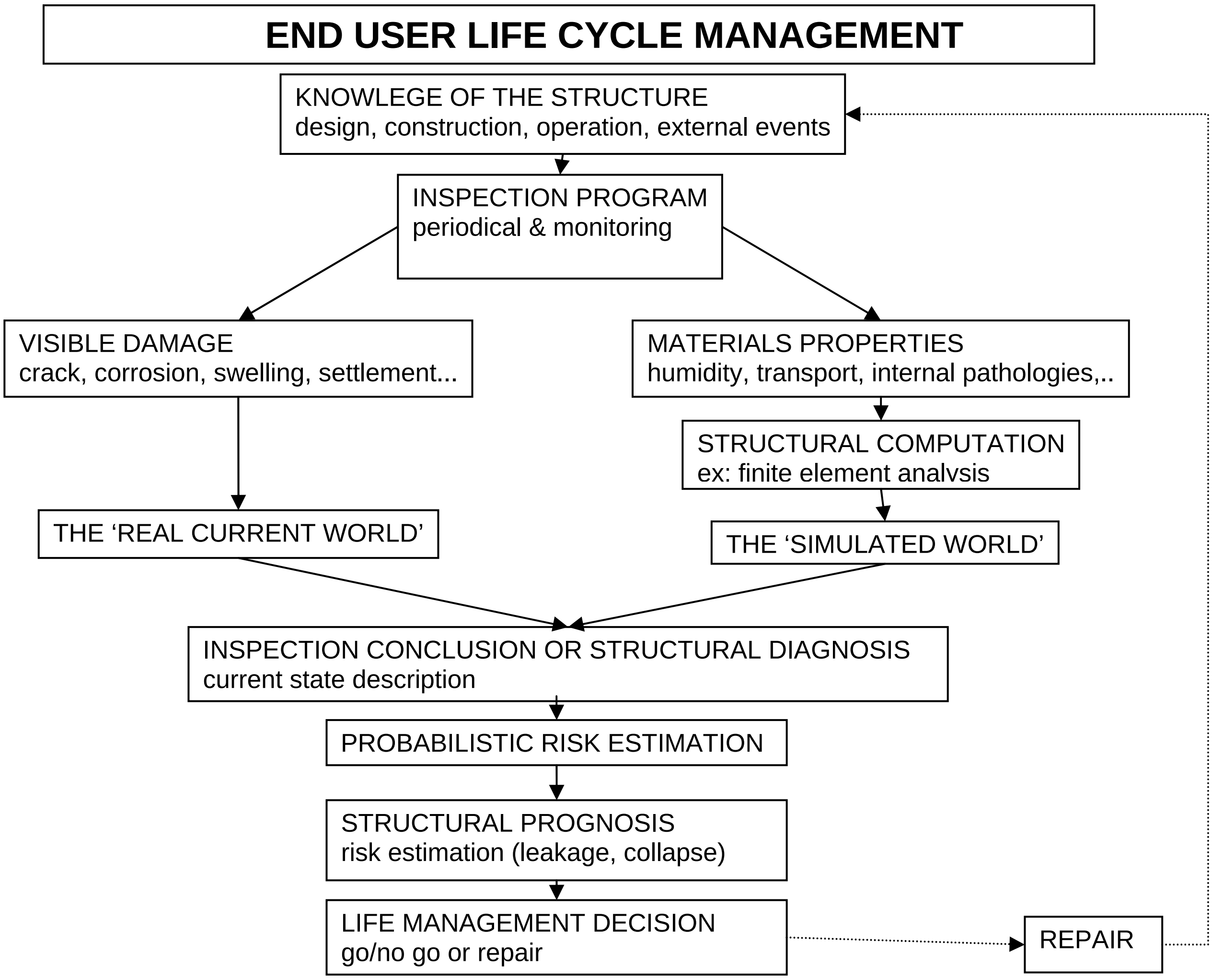
Reference

KLOMÍNSKÝ, J. et al. (2005): Geological and structural characteristics of granitoids in water-supply tunnels in Jizera mountains period 2004-2005 (multidisciplinary research). Czech geological survey. 159 p. (In Czech).

PP.10: End User Lifecycle Management Flowchart

Jean-Marie Hénault, EDF, France

Life extension and life cycle management are key objectives of operators of nuclear power plants (NPP). Continuous safe operation of commercial NPPs is economically desirable for operators and necessary to satisfy the needs of the general public. Furthermore, extension of the operation of NPPs beyond their original design life is critical to ensure continuous reliability of the electric power infrastructure in many countries, particularly as demand is predicted to grow with time. In light of this, some countries have begun the process of life extension to extend operating lifetimes of first-generation NPPs from 40 to 60 years. Up to now, the approach to life cycle management for civil infrastructure varies from plant to plant and operational issues are treated episodically. To move on to a more global approach, EDF decided to adopt a general flowchart, described below, to manage the long term operation of its NPP.



PP.11: Biosensing for Groundwater Radionuclides: Uranyl-238 and Surface Layer Proteins

David J. R. Conroy, Paul A. Millner, Dr Doug I. Stewart, University of Leeds, UK

Radioactive waste contamination into the environment is a global problem. An increasing amount of processed waste buried in legacy sites from the 40's to 70's is escaping into the environment due to aging and failed storage. Due to the current limitations of total remediation strategies biosensing holds potential for continual site monitoring with more rapid response.

A combinatory approach to the problem implementing electrochemical analysis, nanotechnology, supra-molecular chemistry and bionanotechnology is being attempted to offer high sensitivity and selectivity.

By combining the sequestering ability of L*ysinibacillus sphaericus* S-layer protein JG-A12 with Electrochemical Impedance Spectroscopy (EIS) the fabrication of novel uranyl (UO_2^{2+}**)** binding protein based biosensors is reported. The new biosensor responds to picomolar levels of aqueous uranyl ions within minutes using *Lysinibacillus sphaericus* JG-A12 S-layer protein tethered to gold electrodes. In comparison to traditional self assembled monolayer based biosensors the porous bioconjugated layer gave greater stability, longer electrode life span and a denser protein layer. Biosensors responded specifically to UO_2^{2+} ions and showed minor interference from Ni^{2+}, Cs^{+}, Cd^{2+} and Co^{2+} with a limit of detection is 10^{-12}M. Chemical modification of JG-A12 protein phosphate and carboxyl groups prevented UO_2^{2+} binding, showing that both moieties are involved in the recognition to UO_2^{2+}.

PP.12:` **Extensive Environmental Monitoring of Ground Gases/Vapours**

Dr. Peter Morris, Salamander, UK

A primary requirement for understanding and predicting the behaviour of complex systems is the ability to observe them. Observation contributes to understanding of processes and, therefore, the predictive power of physically based models but also provides calibration data vital for more empirical models. The heterogeneity in composition and large size of environmental systems makes their behaviour complex, whilst the same factors make its representative observation difficult. Gas/vapours in the subsurface is a typical example of an environmental system, the predictability of which has been limited by insufficient observation.

Typically ground-gas/vapours regimes are monitored by discrete measurements from which representative ground gas concentrations are inferred. It is because system data is poorly resolved spatially and temporally that the uncertainties in these inferences remain large. Spatial resolution can only be improved by deploying multiple devices and temporal resolution can only be improved by increasing sampling frequency. Historically improving data quality has been very expensive however, recent technological advances has allowed the development of a continuous gas monitoring device, the GasClam.

Using this device continuous data has been collected from a range sites where only discrete measurements had previously been made. The continuous data reveals how variable gas regimes are, highlighting the amount of information that is missing during typical monitoring programmes. The availability of additional data not only makes it possible to observe the true gas regime but also more importantly to identify the processes responsible for gas generation and migration. This information will be critical in understanding carbon sequestration, monitoring green house gas emissions and improving hazardous gas and vapour risk models. Furthermore, should the ability to predict be insufficiently developed for wholly proactive management, this capability for high resolution data collection is integrated with M2M telemetry thereby allowing the most efficient reactive management.

PP.13: Fibre-optic Sensors at PRACLAY

Jan Verstricht, Euridice, Belgium

EURIDICE is preparing a simulation at near-real scale of a disposal gallery for heat-generating, high-level radioactive waste. The PRACLAY Gallery has been constructed for this programme as a part of the HADES Underground Research Facility in Mol, Belgium. It is currently being instrumented before it will be heated for a period of 10 years. During this period, temperatures inside the gallery could exceed 100 °C (in particular near the heating elements), and the water pressure in the saturated gallery might attain values of about 3 MPa.

In addition to the more conventional sensors, two types of fibre optic (FO) sensing techniques are being deployed for monitoring of the gallery. FO sensing has been selected for its assets such as simplicity (the fibre is the sensor, with the sophisticated read-out part located at an accessible place), the possibility to span long distances, intrinsic multiplexing and distributed monitoring minimising the number of cables, which might cause weaknesses to a monitoring concept for the future disposal system.

The first FO sensor type consists of long-base (5 and 10 m long) SOFO® interferometric sensors. One set is installed in boreholes from the PRACLAY Gallery. Another set (three sensors in series) is installed inside this gallery. These sensors will monitor the expansions that we expect to occur - mainly due to the heating. The second type of FO is a distributed FO sensor (based on Brillouin or Raman scattering) to monitor the temperature field inside the PRACLAY Gallery. One such fibre will allow to obtain data that are equivalent with many tens of single points.

In addition to the generated measurement data, this set-up will allow to test these rather novel sensors under conditions, in particular the elevated water pressure and temperatures, that resemble the actual situation of a disposal site. We plan to finish the installation (backfilling and closure of the gallery) by the end of 2010, so that the heating can start in 2011.

PP.14: **SOTA of Wireless Sensor and Transmission Networks**

Jose-Luis Garcia-Sineriz, Aitemin, Spain

Monitoring is widely accepted as a key aspect of disposal of HLW and safety requirements call for a non-intrusive, wireless monitoring system in order to avoid potential flow-paths along cabling that could jeopardise the sealing function of the engineered and natural barriers.

The objective of the on-going research is to develop a wireless sensor and transmission network system totally non-intrusive, where no physical paths were required through the sealing element, capable of providing bi-directional communication and using very low power devices to guarantee long lifetime of operation.

The wireless sensors will be located inside a sealed area of the disposal facility, within a buffer or backfill, and will periodically send their information to a receiver located in a safe zone behind a thick concrete wall (the sealing element). In addition, more sensors could be embedded in the rock.

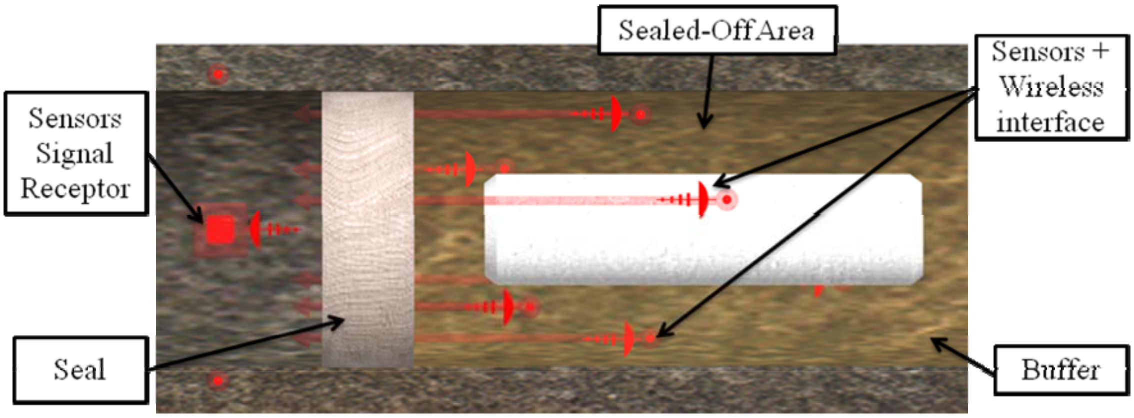


Figure 1: Overview of the proposed monitoring system concept

The proposed method has evident advantages when compared with the more traditional ones, wireless and optic, as can be shown at Table 1.

Table 1: Wireless vs. optic/wireless comparison.

	Wireless	**Optic/Wired**
PROs	Totally non-intrusive method. No physical paths required through the sealing system. The devices can be totally watertight.	High speed communication. Capable of transmitting energy to the sensor element from an external source. Low current consumption elements.
CONs	Wireless signal propagation is affected by physical parameters (humidity, media density, etc.) Lower data rate than other technologies (e.g. optic methods). High power consumption during transmission.	Partially non-intrusive method (optic/wires needed). Low immunity to harsh environment conditions (dust particles, condensation and radiation).

One key point when designing a wireless system is to determine which frequency is the most suitable for this application. Table 2 shows a comparison between high (UHF) and low (ULF, SLF, ELF) frequency bands. Highlighted in red are those aspects that would mean an obstacle for the implementation of the monitoring system and in green those that could present favour points or advantages.

Table 2: High and low frequencies capabilities comparison.

High Frequency Wireless Systems (UHF)	Low Frequency Wireless Systems (ULF, SLF, ELF)
Pros	**Pros**
Higher data rate. **Shorter transmission time.** **Lower power consumption.** **Small size aerials (lower wavelength).** **Wide range of devices available on the market aimed for monitoring applications.**	**Very low attenuation though solid materials.** **High penetration capabilities (used on commercial *"through the earth"* systems).** **High tolerance to water or humid environments.**
Cons	**Cons**
Lower penetration capabilities. **Very low tolerance to the presence of water or humidity (especially 2.4 GHz).**	**Very large wavelength (not suitable for confined spaces).** **Low data rate.** **Higher power requirements.** **Not recommendable for wireless sensor networks (WSN).**

The basic guidelines to be taken into account for the development of wireless sensor are as follows:

- Design based on multi-sensor wireless hub.
- Smart power management.
- Long lifetime.
- Designed to work in harsh environments.
- Self-diagnostic and self-failure detection.
- Pre-transmission signal analysis (DSP techniques).

Each wireless node will be capable of powering and reading the measures of at least 3 sensors, performing a previous analysis of the signal and detecting possible measurement failures, and repeating the process when necessary (Figure 2).

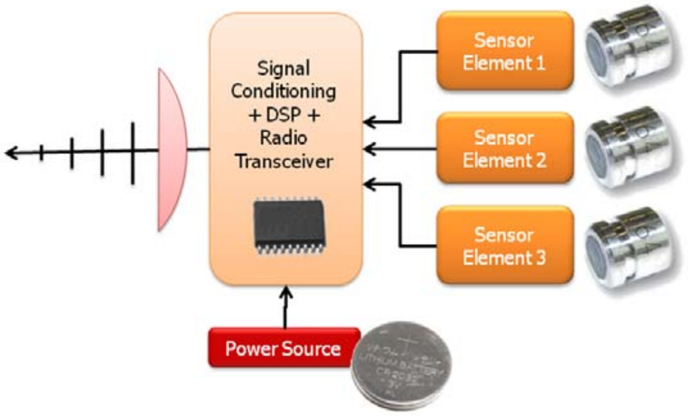


Figure 2: Wireless multi-sensor hub concept.

Figure 3 illustrates about the attenuation of the candidate frequencies through different materials.

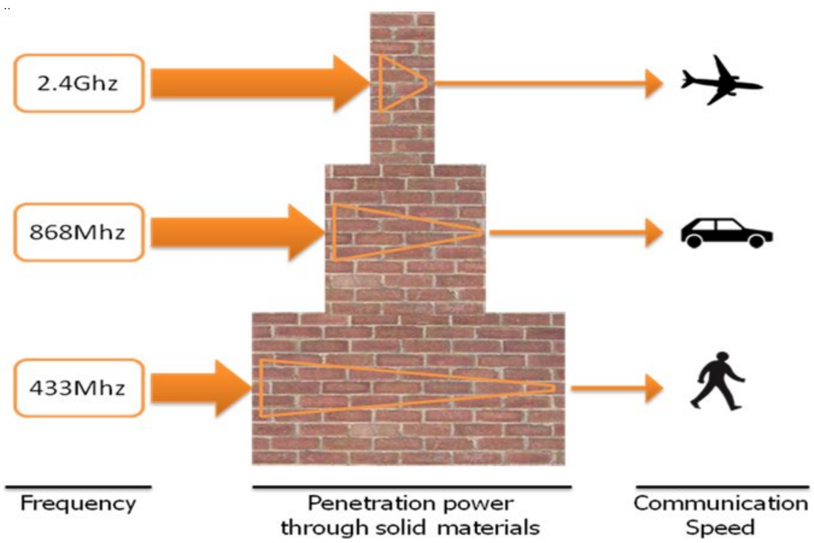


Figure 3: Attenuation of candidate frequencies.

Regarding the communication protocol that could be used for each frequency, the 2.4 GHz will allow the use of protocols based on the standard IEEE 802.15.4 (ZigBee and others). Some 868 MHz transceivers fulfilling this standard are being developed but the technology is not mature enough yet, so the use of frequencies lower than 2.4 GHz calls for the development of a proprietary protocol for the communication system.

PP.15: **Integrated Optical Sensor Networks : Miniaturized Sensors for a Wide Range Of Applications**

Renaud-Goud Ph., Blaize S., Leblond G., Bruyant A., Royer P., UTT, France

Developing large-scale sensor networks demands compact and easily readable sensors.

Integrated optical sensors match those requirements. They have a small footprint, their networking ability benefits from advances in telecommunication optics, and many optical sensing methods have already shown their potentialities.

We will describe a specific optical sensor system developed by the ANDRA (Agence nationale pour la gestion des déchets radioactifs) and the LNIO (Laboratoire de Nanotechnologie et d'Instrumentation Optique). It plans to use micro-cavity enhanced selective gas sensors, and a new kind of integrated optical spectrometer (SWIFTS: Stationary Wave Integrated Fourier Transform Spectrometer) that can be used to interrogate those sensors (Figure 1).

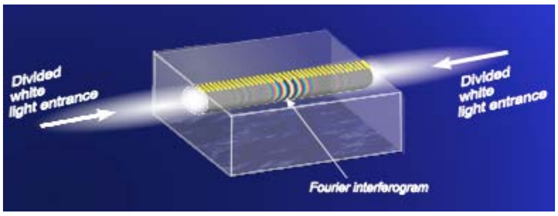


Figure 1: Interference principle of the SWIFTS.

PP.16: **Sensor Technologies for Packages, Storage and Geological Disposal of Radioactive Waste**

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Safe packaging, transport, storage, and disposal of radioactive waste are key activities of a complete radioactive waste management system. National and international regulations (e.g. published by IAEA) require comprehensive monitoring of these activities. Used monitoring systems are mainly based on well-known sensors technologies. BAM is developing innovative monitoring systems and sensors for transport and storage of dangerous goods (mainly chemicals) which may offer new and advanced measuring capabilities also in the field of radioactive waste management.

The integrity of a package for radioactive waste must be ensured during all time. It is therefore important to have methods available for monitoring the condition of such packages so that at the end of the storage period the packages are in a form which is suitable for safe transport, handling and final disposal. A typical monitoring programme for a waste storage comprises two main topics: characterising the environmental conditions (e.g. air and surface temperature, relative humidity, radiation, gas concentration) and monitoring any changes of the packages condition (e.g. surface strain or deformation, surface corrosion). In case of anomalies of a package some of the parameters should be measurable by remote sensing techniques. To safeguard the road transport and package of dangerous goods, a monitoring system based on sensor enabled RFID tags and an online-link to the official data base for dangerous goods is under development at BAM. The RFID tags are placed on the package and contain information like packaging-EPC, ERI-Cards, UN number, quantity, product name, technical name, batch, filler, approved temperature range. In combination with an onboard unit of the truck several parameters (e.g. temperature monitoring, crash detection, tilt sensor, panic button, dangerous goods routing) are observed during transport and in case of emergency information is transmitted to relevant authorities. The sensor enabled RFID tag can be connected with sensors for a wide variety of quantities, incl. strain and radiation.

Accidents with dangerous goods are often accompanied by volitional and unintentional emission of toxic gas. In order to evacuate the potentially polluted area, quick and substantial information is needed about the 3D-concentration of the toxic cloud, the direction and travelling speed of the cloud. For these purpose a micro-drone for the characterisation and self-optimizing search of gaseous hazardous substance sources is under development. It is based on a light weight quadro-copter in combination with a multi-gas sensor. The compact design and the excellent manoeuvrability of remote-controlled quadrocopters allow precise navigation and enable also the possibility to enter small passages or operate in warehouses. The gas sensor comprises of a multi-gas sensor for five different gases. Different sensors can be used, which allows users to customize it for their application. A sensor head for radiation measurement is also available.

When a major component of a civil engineering structure suddenly fails, a partial or total collapse will be the consequence. If it is a bridge or a large hall, then people in particular are at high risk. The increasing age of bridges and the growing volume of traffic (particularly heavy trucks) which they are expected to carry are in clear contradiction to each other. Thus the probability increases that the load-bearing capacity of a bridge decreases rapidly and often unnoticed with sometimes awful consequences. In order to prevent such accidents, BAM is developing a special radio-based, self-configuring, multi-hop measuring system in cooperation with the Berlin-based ScatterWeb Company. The system consists of a number of identically designed sensor nodes which are self-sustaining, need no wiring, can act as both transmitters and receivers and are equipped with a special sensor technology making long-term monitoring of buildings or engineering facilities possible. The sensor unit uses strain gauges for stress analysis and contains interfaces for additional sensors. The system in particular applies to buildings and structures for transport and traffic and large-scale industrial facilities where a subsequent wiring installation is difficult or impossible. It can easily be adapted to similar measuring tasks in geological repositories for radioactive waste. Monitoring of rock mechanics, hydrogeological monitoring, monitoring of hydrogeochemistry can be performed with high flexibility, very short installation time and no wiring needs.

PP.17: Some Examples of the Application of Monitoring Techniques and Sensors to Radioactive Waste Stores

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Monitoring techniques and sensors applicable to higher-activity radioactive waste (HAW) stores focus on the:

- Structural integrity of the facility.
- Operability of plant and equipment.
- Environmental conditions within the store.
- Discharges from ventilation systems and/or drains, where applicable.

Sensors and techniques that have been, or have the potential to be, used in HAW stores were identified during a review of performance and monitoring of interim HAW stores[1] in the UK, France, the Netherlands, Spain and Switzerland. Focusing on techniques for monitoring the structural integrity and the operability of plant and equipment within the store, some examples of the following will be presented:

- Embedded corrosion sensors for monitoring the condition of metal reinforcement in the concrete structure.
- Fibre optic sensors for monitoring corrosion, strain and displacement and for detection of cracks in concrete.
- Visual inspection techniques to identify general corrosion and, depending on the severity, surface pitting or cracking in concrete or metal.
- The monitoring techniques employed in HAW stores are dependent on a number of factors, including store design, management practices and the waste packages being stored.

[1] A report entitled "*Higher Activity Waste – Interim Store Performance and Monitoring*" was produced for the UK Nuclear Decommissioning Authority (NDA) Integrated Project Team on Interim Storage by Galson Sciences Limited and UKAEA Limited. The review was funded through the NDA's Direct Research Portfolio (Contract no. CJ000104).

PP.18 In situ monitoring at the Josef Underground Facility

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The Czech Technical University (CTU) in Prague has recently opened a facility dedicated to practical teaching, training and, importantly, to research. The Josef Underground Educational Facility (www.uef-josef.eu) is operated by the Centre of Experimental Geotechnics, Faculty of Civil Engineering.

The facility is located in central Bohemia, Czech Republic and consists of an underground complex excavated during the 1980s to explore the potential for gold extraction in the area. In 2007 the gallery was converted into a unique scientific facility the main role of which is to provide an opportunity for practical experience in the fields of underground structures, geotechnics, surveying and geology. Arguably, the Josef UEF's most important role, as well as one of the FCE's long-term priorities, is to provide for high-level underground in situ research.

The deployment of high-quality monitoring technology in the underground areas is a challenging task and has to satisfy the specific requirements set by the environment. The system deployed at the Josef UEF has been designed as a modular system using one common infrastructure.

The main requirements of the system are to provide remote monitoring and access to experiments being performed in the underground facility from anywhere in the world, video surveillance and telephone communication with the potential to extend the system to include additional functions.

Following a thorough evaluation process, Ethernet technology was chosen together with TCP/IP protocols for the network backend. Metallic cables are used for local distribution and fibre optics for the backbone. Two identical networks have been built (and are being constantly enlarged) – one dedicated solely to measurements and the second for other functions. These two networks are not connected under normal circumstances for security reasons however if needed parts of the networks could easily be swapped or interconnected to serve as a full hardware backup. The use of IP protocols provides a high degree of flexibility at a reasonable price.

A good example of how the infrastructure of the Josef UEF is employed is provided by the TIMODAZ experiment measurement system. As part of the European TIMODAZ project, a physical model of a deep underground repository disposal tunnel has been constructed. The in situ physical model was constructed using the prefabricated lining of a Belgian disposal tunnel resulting from the Praclay project.

The whole of the experiment is fully instrumented. Over 250 sensors measure the most significant parameters: temperature (thermistors; integrated-circuit temperature sensors), stress/load (hydraulic pressure cells), deformation (vibrating string gauges) and displacement (Conductive Linear Position Transducers). In addition, the power consumption of the heating system is also measured.

The sensors are connected to data loggers which convert analogue signals into digital form. The data loggers are connected to the Josef UEF measurement network using RS232/Ethernet convertors. All the main logics reside in a server located within the surface facility. The server has three main functions – to gather data from the sensors (via data loggers), to store the measured data for further use and to present the data to the end-user.

Data is gathered using daemon programs usually at intervals of 10 minutes (some sensors even more frequently) and immediately stored in the database without any processing. The database contains raw data with UTC timestamps as well as all the necessary information on the sensors themselves such as sensor type, calibration data and position within the experiment. The frontend is web-based and allows the end-user to monitor the experiment almost in real time as the most up-to-date data is always available. The data from the sensors is recalculated from the raw data when requested by the user. This allows a high degree of flexibility in terms of sensor management since sensor changes are instant and errors do not influence the measured data. Open software is used almost exclusively for the measurement system. The system is Linux-based with the MySQL database serving as the data store and Apache as the web server. The experiment is connected to the internet so that the measurement results are readily available not only to the various partners involved, but also to the general public (http://www.uef-josef.eu).

IP-based cameras were chosen for video surveillance purposes which eliminated the problems of having long video cables and allowed greater flexibility with regard to camera placement. A further advantage lies in the ease with which the video system can be extended – adding a new camera involves simply connecting it to the common network.

The telephone system is fully digitalised, i.e. VoIP based and uses the SIP protocol with open source Asterisk PBX. All the phones are either digital or are connected via the VoIP gateways attached to them. The need for a lengthy analogue cable network is eliminated since a common infrastructure is used.

The VoIP is also used for the Josef UEF external telephone connection as there are no analogue lines available.

PP.19: **Wireless Transmission Monitoring for Geological Disposal**

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In order to confirm the safety of geological disposal, the authors have been studying the feasibility of monitoring the phenomenological evolution behind the bentonite seals emplaced in various locations in tunnels. Monitoring cables that pass through or around seals could affect the confinement performance of the seals. So as to solve this problem, the authors propose a monitoring technique that uses a wireless data transmission system.

Wireless communication applications such as radio and television broadcasting, and cellular phone communication ordinarily use high-frequency electromagnetic waves (from several kHz to GHz). However, in media with electromagnetic conductivity, such as rock mass and bentonite, high-frequency electromagnetic waves are excessively attenuated. Consequently, the authors have been developing a wireless data transmission system that can be applied in media such as rock mass or bentonite by using a very low frequency (VLF, approximately 1 kHz) electromagnetic wave as a data carrier. Based on an in situ transmission experiment and an analytical assessment, this study presents concepts and advantages related to wireless transmission monitoring of geological disposal.

PP.20: Wireless Data Transmission Technology from Repository to Surface

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In the Netherlands, the retrievability of waste is an essential requirement for the geologic disposal of nuclear waste. To monitor the evolution of a waste disposal facility in the post-closure phase, an autonomous wireless monitoring infrastructure is necessary. A system for the wireless transmission of data from the repository to the surface, bridging 500 m of geological media, is an essential part of such a monitoring infrastructure. Within the EU FP7 project MoDeRn, NRG will develop and demonstrate techniques for the wireless transmission of data from the underground to the surface by the use of very low frequency magnetic waves.

Energy efficiency is a relevant issue for the autonomous monitoring infrastructure. To quantify and optimize the energy efficiency of the magneto-inductive technique is the main objective of the contribution. The work is divided in three phases:

1. Characterization of magneto-inductive technique.
2. Optimizing energy efficiency.
3. Bidirectional transmission set-up.

In the first phase, the necessary hardware will be designed and assembled and a first *proof-of-principle* will be performed in the Netherlands to demonstrate the proper working of the transmitter-receiver set-up. Prior to the experiments performed at the HADES URL (Mol, Belgium), the site-specific magnetic background noise at the surface will be characterized and the frequency-dependent signal attenuation by the geologic medium between the HADES URL and the surface will be measured. Based on these data, the most favourable signal transmission frequencies will be derived and tested by data transmission experiments from the HADES URL to the surface.

In the second phase of the NRG contribution, the energy usage of the data transmission technique will be optimized: dependent on the results reached so far, several techniques to increase the energy efficiency may be tested:

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

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

PP.21: **Development of Non-intrusive Monitoring using Cross-hole Seismic Tomography**

Stefano Marelli, ETH Zurich, Switzerland

PP.22: Latest Technologies for Microseimic, Acoustic Emission and Ultrasonic Monitoring in Radioactive Waste Disposal and Feasibility Studies

Juan Reyes-Mentes, Applied Seismology Consultants, UK

Over the past 20 years microseismic, acoustic emission (AE) and ultrasonic monitoring have become an essential tool in research and commercial projects of permanent disposal of hazardous waste in underground engineered structures. Microseismic, AE and ultrasonic technologies are scaled seismic investigations that provide remote methods of examining the disturbance and damage evolution induced in a rock mass experiencing changes in operating conditions of a radioactive waste repository. The technologies allow the volumes of disturbance and damage to be delineated and quantified, and provide measured data for the validation of numerical models that predict the effects of the environmental conditions on the rock mass, including mechanical, thermal and hydraulic stresses, and chemical and biological processes.

Examples of geological repositories in crystalline environments are AECL's Underground Research Laboratory (URL) in Canada and SKB's Hard Rock Laboratory (HRL) in Sweden. At the Tunnel Sealing Experiment (TSX) at AECL's URL two arrays were set up: one AE system was installed in the rock volume adjacent to the clay bulkhead; another was contained within the concrete bulkhead and adjacent rock-mass. The concrete results showed failure in the concrete during curing and the fracture defined by the AEs was used to direct the injection of grout. At SKB's HRL acoustic emission monitoring and ultrasonic surveying have been conducted around the ZEDEX, canister Retrieval Test and APSE experiments. At the Prototype Repository, ASC monitored the excavation of the deposition boreholes during excavation in 1999 and have been managing the system and providing reports on the AE and ultrasonic status from 2003 onwards. This has provided a record of changes to velocities and AE event rates during periods of heating and pressurization.

At the Tournemire Experimental Tunnel and Tressange OMNIBUS EU project ASC has used tools in soft rock environments. ASC is currently involved as a research partner of the TIMODAZ project which is co-funded by the European Commission as part of the sixth EURATOM research and training Framework Programme (FP6) on nuclear energy. Ultrasonic surveys are used to 'actively' examine the rock velocity changes around the PRACLAY heater test. Amplitude and velocity changes on the ray paths are interpreted using Effective Medium Theory models in terms of changes in the properties of the rock affecting its capability for sealing and isolating the repository volume.