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State of Art Report on Monitoring Technology

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List of Acronyms

EBS: Engineered Barrier System
EC: European Commission
GTS: Grimsel Test Site
HLW: High Level Waste
HRL: Äspö Hard Rock Laboratory
IAEA: International Atomic Energy Agency
ILW: Intermediate Level Waste
MTL: Mont Terri Underground Rock Laboratory
RTD: Research and Technology Development
THMC: Thermal, Hydro, Mechanical and Chemical
URL: Underground Research Laboratory
WP: Work package

List of key Terms

A list of internally accepted definitions of key terms used to describe the technical specifications of monitoring equipment is included as annex I. The terms included so far are as follows:

Accuracy: indicates proximity of measurement results to the true value. Note that for repository monitoring this can be a rather theoretical entity.
Analytical quality control (AQC): all those processes and procedures designed to ensure that the results of laboratory analysis are consistent, comparable, accurate and within specified limits of precision.
Bias: non-random or directed effects caused by a factor or factors unrelated to the measured parameter.
Confounding variable: an extraneous variable in a statistical model that correlates (positively or negatively) with both the dependent variable and the independent variable.
Correction: value added algebraically to the uncorrected result of a measurement to compensate for systematic error. The correction is equal to the negative of the estimated systematic error. Since the systematic error cannot be known perfectly, the compensation cannot be complete.
Correction factor: numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error.
Dead Band: the range through which an input can be varied without observable response
Drift: an undesired change in the output-input (signal-real value) relationship over a period of time
Error (of measurement): result of a measurement minus the value of the true value.
Failure: state or condition of not meeting an intended performance.
Hysteresis: that property of an element evidenced by the dependence of the output for a given excursion of the input, on the history of prior excursions and the direction of the current traverse.
Linearity: the closeness to which a curve approximates a straight line.
Method: the application of a technique for a specific measurement in a specific environment, including all hardware components necessary to convert sensor signals to (digital) data (wiring, connectors, converters).
Precision: of measurement is related to the **repeatability** or **reproducibility** of the measurement. Anyhow, the latter are more accurate expressions that should be preferred.
Procedure: a set of written directions defining how to apply a method to a particular environment, including information on placement of sensors and other hardware, handling of cross-sensitivities, and validating results. A method may have several procedures as it can be adapted to a specific need.

Quality assurance (QA): planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled. It is the systematic measurement, comparison with a standard, monitoring of processes and an associated feedback loop that confers error prevention

Random error: result of a measurement minus the mean that would result from an infinite number of measurements of the same parameter carried out under repeatability conditions.

Reliability: ability of a device or system to perform a required function under stated conditions for a specified period of time.

Repeatability (of results of measurements): closeness of the agreement between the results of successive measurements of the same parameter carried out under the same conditions of measurement.

Reproducibility (of results of measurements): closeness of the agreement between the results of measurements of the same parameter carried out under changed conditions of measurement.

Redundancy: the duplication of critical components or functions of a system with the intention of increasing reliability of the system. There are several forms of redundancy, these are:

- Hardware redundancy (duplication, triplication, etc. of systems)
- Distinct functional redundancy, such as both mechanical and hydraulic braking in a car
- Information redundancy, see error detection and correction methods
- Time redundancy, including transient fault detection methods
- Software redundancy

Resolution: the smallest change in the underlying physical quantity that produces a response in the measurement.

Sensitivity: The ratio of change in output magnitude (signal) to the change in input (real value) which causes it after the steady state has been reached.

Systematic error: mean value that would result from an infinite number of measurements of the same parameter carried out under repeatability conditions minus the (real) value of the parameter.

Technique: any chemical or physical principle used to measure a parameter. There are often several possible techniques available to measure one parameter.

Technology Readiness Level (TRL): a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. Terminology/methodology is used in different fields of work with slightly different definitions, as there is no general definition of the TRLs. Nine levels of readiness are defined, from the lowest, TRL1 “Basic principles observed and reported”, to the highest, TRL9, which for this field of application could be defined as “Actual monitoring system operated in a full scale disposal facility”.

Uncertainty: A state of having limited knowledge where it is impossible to exactly describe the existing state, a future outcome, or more than one possible outcome. For measurement methods, it defines the confidence interval of the expected outcome. Uncertainty depends on both the accuracy and precision of the measurement instrument. The lower the accuracy and precision of an instrument, the larger the measurement uncertainty is. Expressing the uncertainty of measurement results normally requires the use of the terms *standard uncertainty*, *combined standard uncertainty*, *expanded uncertainty*, or their "relative" forms. Notice that precision is often determined as the standard deviation of the repeated measures of a given value. However, this method is correct only when the instrument is accurate. When it is inaccurate, the uncertainty is larger than the standard deviation of the repeated measures, and it appears evident that the uncertainty does not depend only on instrumental precision.

1. Introduction

This report summarized the current state-of-the-art of monitoring technology related to the deep geological disposal of radioactive waste as part of the European 7th framework project "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn). The State of Art report is intended to:

- Provide an introduction about (i) the parameters of interest for monitoring; (ii) the components that might need monitoring, and (iii) the associated requirements and constraints
- Present an overview of relevant state of art on technologies relevant for use in a repository context[1]
- Justify this relevance with available references, feedback and experience
- Summarize advantages and disadvantages of available technologies for repository monitoring
- Propose R&D leads to remove some of the disadvantages
- Conclude on feasibility and limitations for repository monitoring

In the next two sections, a high-level overview of monitoring in the context of the disposal of radioactive waste in geological repositories is given to provide the necessary conceptual context to the discussions in subsequent sections of this report. In Section 1.3, general topics related to repository monitoring are shortly presented, followed by an overview how the MoDeRn project has addressed these topics (Section 1.4). Section 1.5 provides the rationale behind this report, and Section 1.6 gives an overview of the structure of the remainder of this report.

1.1 Geological Disposal and the Safety Case

Currently, geological disposal is internationally assumed to be the only feasible option for the safe disposal of long-lived radioactive waste in the long term, in order to protect man and the environment. The long-term safety of geological disposal is currently demonstrated by the internationally used methodology of the "Safety Case" [1], [2], [3] that provided a contextual structure that is also assumed to be useful for the elaboration of monitoring strategies (see MoDeRn Deliverable D-1.2.1 [4]). In the following paragraphs the principles of the Safety Case are described, including a deeper analysis of role of monitoring in geological disposal within a Safety Case, examples of monitoring objectives and different options/strategies available to perform the monitoring and that were used to classify the applicable techniques.

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 geological disposal of these radioactive wastes is to protect people and the environment from harmful effects of ionising radiation [5].

Geological disposal aims to isolate and contain waste through appropriate design and operation of the facility, through sitting 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. Besides the EBS, geological

[1] Note that not all the reviewed techniques will be required to monitor a repository

barrier(s) as the host rock that enclosed the facility, isolates the waste from the biosphere, contains and retards radionuclides and maintain the protective function of the EBS. Any disposal concept and its engineered barriers must be tailored to the specific geological environment in which it is to function.

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 [6]. 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 [6].

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 in these programmes may include:

- 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.

References

[1] Nuclear Energy Agency. Confidence in the Long-term Safety of Deep Geological Repositories. Its Development and Communication. OECD, Paris, 1999.

[2] Nuclear Energy Agency. Post-closure Safety Case for Geological repositories: Nature and Purpose. NEA report 3679, OECD, Paris, 2004.

[3] IAEA. The Safety Case and Safety Assessment for Disposal of Radioactive Waste. IAEA Safety Standard Series, Draft Safety Guide No. DS 355, Vienna, June 2011.

[4] MoDeRn Project (2013). Monitoring objectives and strategies report.

[5] IAEA (2006a). Fundamental Safety Principles. IAEA Safety Standards for Protecting People and the Environment. Safety Fundamentals No. SF-1. IAEA Vienna.

[6] IAEA (2006b). Geological Disposal of Radioactive Waste. IAEA Safety Standards for Protecting People and the Environment. Safety Requirements No. WS-R-4. IAEA Vienna.

1.2 Role of monitoring of geological disposals in the Safety Case

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. A general definition of the term "monitoring" within the context of geological disposal has been defined in the Monitoring ETN [7] 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."*

Identified monitoring objectives/roles 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 IAEA has defined the role of monitoring programmes in the safe disposal of radioactive waste [6] as follows:

- *"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."*

1.3 General topics on repository monitoring

The work undertaken as part of the MoDeRn Project is focusing mainly on monitoring in support of long-term safety and there are several challenges to develop 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. 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, 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).

Further information on monitoring of geological repositories can be found in MoDeRn Deliverables D-1.2.1 [4] and D-2.1.1 [8]. For a general reference, the IAEA TECDOC [9] and the ETN-report on monitoring [10] can be used.

References

[7] EC (2004). The joint EC/NEA Engineered Barrier System Project: Synthesis Report (EBSSYN). Final Report, no. EUR 24232. EC, Luxembourg.

[8] MoDeRn Project (2011). Technical requirements report.

[9] IAEA (2001). Monitoring of Geological Repositories for High Level Radioactive Waste. IAEA-TECDOC-1208, IAEA Vienna.

[10] EC (2004). The joint EC/NEA Engineered Barrier System Project: Synthesis Report (EBSSYN). Final Report, no. EUR 24232. EC, Luxembourg.

1.4 The MoDeRn project

The main objective of the EC Seventh Framework Programme "Monitoring Developments for Safe Repository Operation and Staged Closure" (MoDeRn) Project is 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 (WP):

- **WP 1, Monitoring Objectives and Strategies:** it 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.
- **WP 2, State-of-the-art and RTD of Relevant Monitoring Technologies:** this work 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 (the subject of this document); it includes a technical workshop involving other monitoring Research and Technological Development (RTD) projects, leading to the identification of RTD techniques that enhance the ability to monitor a repository.
- **WP 3, *In situ* Demonstration of Innovative Monitoring Technologies:** the objective is to 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.
- **WP 4, Case Study of Monitoring at All Stages of the Disposal System:** this WP 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.
- **WP 5: Dissemination of Results:** the outcome of this work will be 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 production and maintenance of a project web site is also included.

- **WP 6: Reference Framework:** The final WP will consolidate results from the previous ones and provide a shared international view on how monitoring may be conducted at the various phases of the disposal process. The relationship of the MoDeRn Monitoring Workflow to work being undertaken in the project is illustrated in Figure 1.

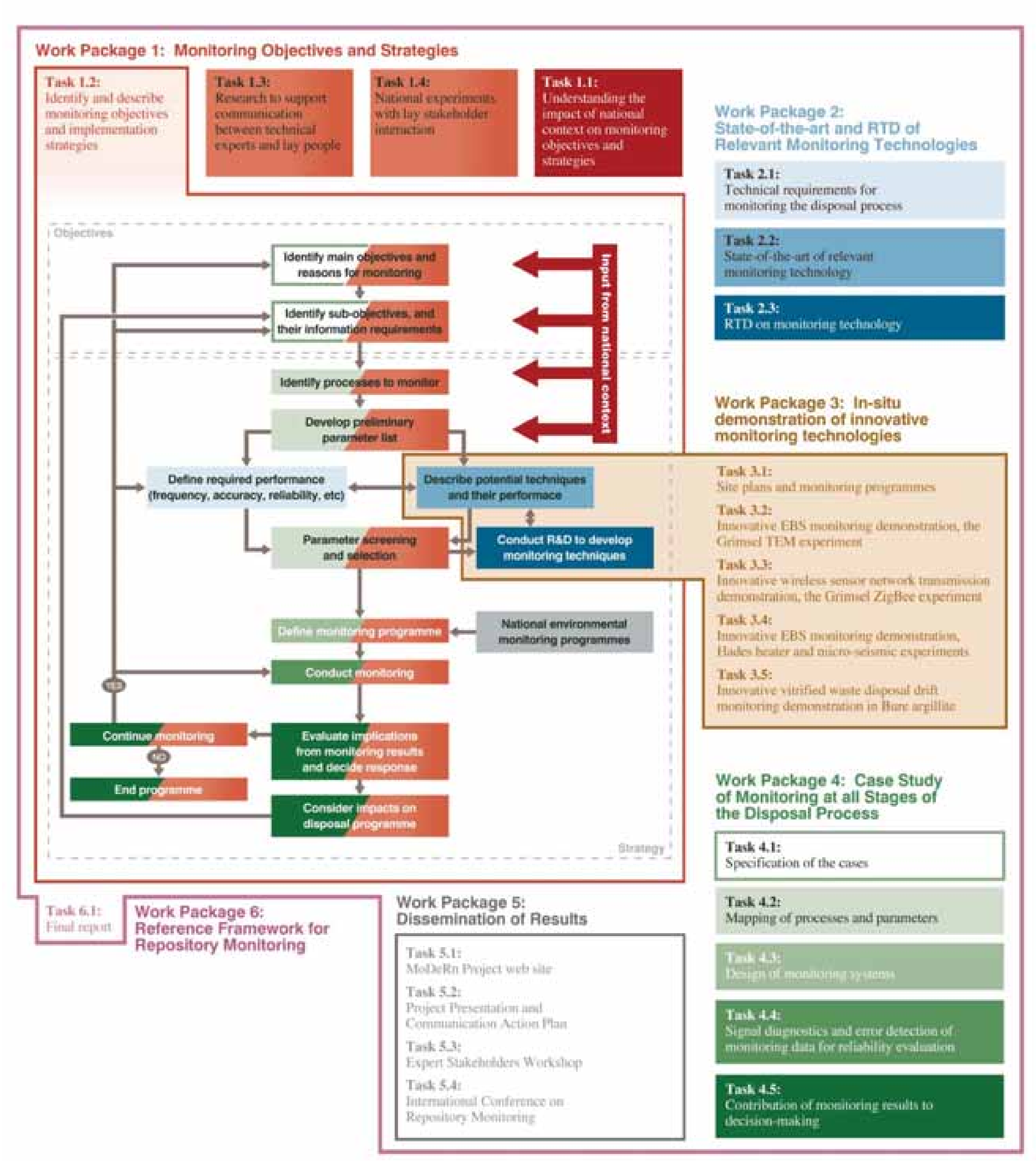

Figure 1: Relationship of the Preliminary MoDeRn Monitoring Workflow to MoDeRn Project work package tasks. Note: ZigBee demonstrator is now High Frequency Wireless one

1.5 Rationale of this report

Providing this state of art of technology will allow the implementer to conduct a realistic analysis: Based on the monitoring needs, and based on an understanding of available technology and different approaches (in-situ, non-intrusive or wireless transmission, borehole based, surface based…), the implementer can provide (i) a realistic description of what and how monitoring can be implemented; can provide (ii) an informed discussion on current, technical limitations. Based on the latter, the implementer can further recommend (iii) where future R&D would be most beneficial and (iv) where only alternative implementation approaches can provide some monitoring information (e.g. from comparable long-term experiments instead of in-situ monitoring).

1.6 Report Structure

The present document provides a synthesis of the existing knowledge on applicable monitoring technologies based on three main sources:

- the applicable knowledge and experiences provided by the project partner [11].
- the results of the Troyes Monitoring Technologies Workshop [12], focused on the applicable knowledge from monitoring applications with similar technical requirements as:
  - URLs and ILW repositories,
  - nuclear power plants operations,
  - mining, oil and gas operations,
  - monitoring of subsurface infrastructures,
  - gas storage,
  - hydrocarbon exploration or
  - CO_2 sequestration and storage.
- the outcome of the RTD and demonstration activities carried out within the MoDeRn project (WP2 & WP3).

Emphasis in this report is placed on sensors, signal and data transmission, and local energy sources, because these are assumed to present the most critical components of a monitoring system. Aspects related to signal diagnosis (tools) have been included too. All topics will be discussed within the specific technical requirements imposed by the context of monitoring in geological repositories.

The report is structured as follows:

- Chapter 1 (this chapter) presents the repository monitoring, describes the background to the MoDeRn project, and the rationale, objectives and structure of this report
- Chapter 2 gives a condensed overview on the main elements of a monitoring programme and discusses main components and approaches for monitoring.
- Chapter 3 provides an extensive overview of the state-of-the-art of monitoring technologies applied in repository monitoring and other related work fields.

- Chapter 4 provides an evaluation of the monitoring techniques presented, highlighting the main areas for improvement in existing technologies, and finally presents the conclusions from this study.

References

[11] AITEMIN (2010). MoDeRn Project: State of Art – Initial (M- 2.2.2.2).

[12] White, M., Morris, J. and Harvey, L. (2010). MoDeRn Project: Workshop on Monitoring Technologies Report (D-2.2.1).

2. Overview of a monitoring programme

2.1 Introduction

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.

2.2 Components, processes and parameters

First step for designing the monitoring programme will consist on analysing the repository components, their safety functions and the related relevant processes to determine the preliminary list of parameters to be included in the monitoring programme. Such preliminary list of relevant parameters will be then screened upon the measurement feasibility to propose the adequate/realistic monitoring programme. This process is accomplished and further described in WP4.

The list included hereafter illustrates about the components and processes that a repository monitoring programme might cover, based on a generic conceptual design for the engineered barrier system of a high-level waste (HLW) repository (see Figure 2).

An example of processes in different parts of a repository that a 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.

- 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.
  - 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.

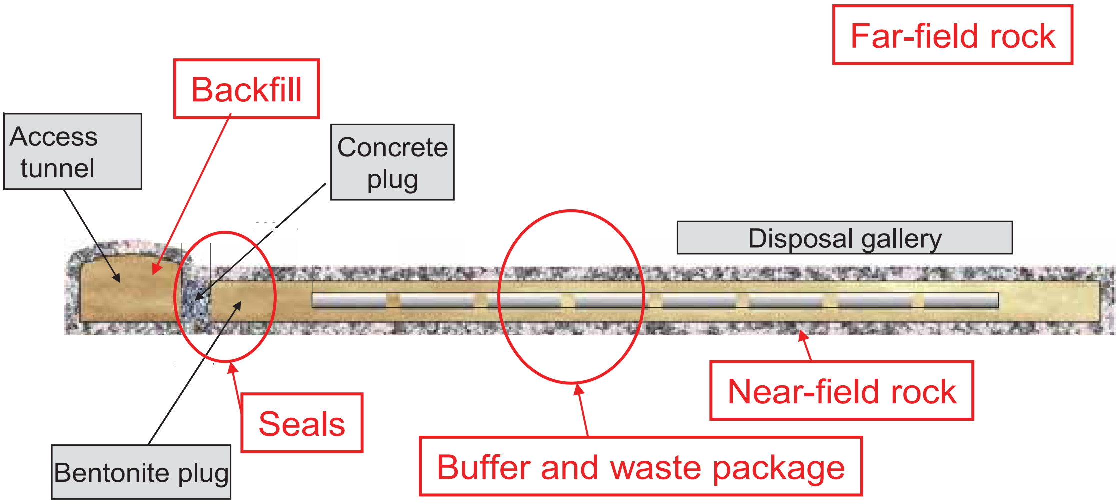

Figure 2: Illustration of the components and layout of a generic conceptual design for the engineered barrier system of a HLW repository.

The definition of technical requirements for the monitoring of a repository will be based on considerations on the potential objectives that must be achieved in a set of given environmental conditions, while respecting repository safety, both operational and post-closure. A list of potential monitoring requirements was provided in MoDeRn Deliverable D-2.1.1 [8] and a preliminary list of parameters of interest for most repository monitoring programs[2] was identified and compiled too:

- Temperature
- Mechanical pressure
- Water content & humidity
- Hydraulic pressure
- Radiation
- Displacement
- Deformation
- Gas concentration (Oxygen, Carbon Dioxide, Hydrogen and Methane)
- Gas pressure
- pH & Eh
- Concentration of colloidal particles
- Alkalinity

Currently, it can be stated that no conclusive list of relevant parameters exists. A workflow to provide such a list for a given programme was developed in WP1, and the usefulness of the approach was evaluated for specific examples (cases) in WP4. Thus, the list of parameters provided above is based in first instance on expert judgement and therefore it should be noted that only a few of them could be required in the real case. It should be noted too that the topics discussed in this report are involuntarily biased by the expertise present by the performance of actual research projects, often performed in-situ, and should not be understood in a way that this list is considered relevant for the purpose of monitoring in a way as addressed in the MoDeRn

[2] Given the variety of national contexts, not all parameters may be necessary or of interest for monitoring on each case, while others related to a very specific objective, may need to be added.

project. Although efforts where made to present a complete enough list, it cannot be excluded that the list of technologies discussed in the next chapter is incomplete.

2.3 Monitoring options/strategies

The current approach to monitoring programmes in the operating phase would place reliance on the use of classical wired instrumentation that should be removed as soon as the different repository areas are being sealed. The general view is that the use of cables for data transmission or energy supply could affect the behaviour of the engineered barriers and therefore they would not be acceptable, unless it can be demonstrated that this is not the case or if monitoring makes use of pilot facilities or a dedicated test disposal drift.

Thus one solution to maintain operational monitoring systems during the early closure phase (repository-based monitoring) is the use of wireless data transmission systems provided with some kind of energy supply to the isolated sensors to allow monitoring information to be provided for long periods after isolation.

It is recognised that, even with some of the proposed solutions being considered in this work, these alternative monitoring systems and monitoring programmes could not be sustained over the very long timescales after repository closure. It is for this reason that safety cases do not rely upon monitoring. However, monitoring systems/programmes will provide a means in the short term for tracking the system and comparing against expectation. Such monitoring systems can provide a basis for confirmation and confidence-building.

The repository-based monitoring, if feasible, will provide information during a relatively short period of time after repository closure and thus complementary monitoring techniques such as monitoring the repository from observation boreholes or from the surface, which can be maintained over longer periods of time, should be considered. Other aerial monitoring systems such as satellite interferometry could also be used to provide monitoring information.

In consequence the applicable monitoring technologies have been structured in the following sections:

- Repository-based monitoring,
- Borehole-based monitoring,
- Surface-based monitoring and
- Aerial or Remote monitoring systems

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

There are well known techniques whose characteristics can be easily found elsewhere and that have been successfully applied for decades (e.g., temperature measurement) which are therefore treated within the document in a succinct way. On the contrary, those techniques that have not been fully described up to date (as the relative humidity measurement) or are more recent or novel (as the fibre optics or the wireless transmission) are described in more detail.

3. Monitoring Technologies

In this section, the state-of-the-art of monitoring technologies suitable for a repository monitoring programme is summarised according to the main sections and parameters identified above. For each parameter a high-level summary of the monitoring technology is provided, covering all or most of the following points:

- A brief rationale: why measuring such parameter
- Available techniques and main characteristics
- Accuracy and range of application
- Long term performance and reliability
- Installation topics
- Particularities
- Data acquisition units
- Conclusions
- References to obtain more details if required

3.1 Repository-based monitoring

There are different approaches to take measures in a repository. Classical wired sensors are the most widely used and represent a standard, reliable and well known solution in most cases. Sensors based on fibre optics have been developed more recently and their use is increasing progressively as they can have some advantages with regard to classical sensors, but still they are wired sensors. Wireless data transmission techniques, based both on low and high frequency bands, in combination with classical sensors are being considered lately to avoid cabling through the repository barriers. All of them are addressed in this section.

3.1.1 Classical wired Sensors

3.1.1.1 Temperature

Why measure temperatures?
Temperature is one of the three key parameters in a repository to monitor and assess the evolution of both engineered and natural barriers through THM models, so an accurate measurement within the repository is essential.

Techniques and signal characteristics.
Available techniques are well known and temperature can be measured via a diverse array of sensors. All of them infer temperature by sensing some change in a physical characteristic. The techniques used/tested so far are:

- Thermocouples,
- Resistance temperature detectors (RTDs)
- Thermistors (used in some sensors for other parameters' compensation).

Other existing sensors, not considered in this section as they are not commonly used in this field of application, are: infrared radiators, bimetallic devices, liquid expansion devices, and change-of-state devices. The main three techniques are described hereafter while fibre optics is included in Section 3.1.2.

Thermocouples consist essentially of two strips or wires made of different metals and joined at one end. Changes in the temperature at that juncture induce a change in electromotive force (emf) between the other ends. As temperature goes up, this output emf of the thermocouple rises, though not necessarily linearly.

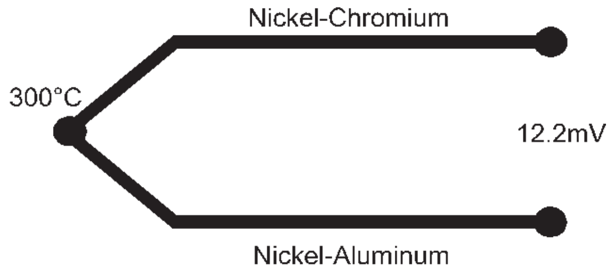

Figure 3: Thermocouple junction.

Thermocouples have plus and minus legs so polarity must be observed. They can be directly connected to a local 2-wire transmitter and copper leads can be run back to the receiving instrument. If the receiving instrument is capable of accepting thermocouple inputs directly, the same thermocouple wire or thermocouple extension wire must be used all the way back to the receiving instrument.

Resistance temperature devices capitalize on the fact that the electrical resistance of a material changes as its temperature changes. Two key types are the metallic devices (RTD's) and thermistors.

RTD's rely on resistance change in a metal, with the resistance rising more or less linearly with temperature. They are positive temperature coefficient (PTC) sensors whose resistance increases with temperature. The main metals in use are platinum and nickel. The most widely used sensor is the 100 ohm or 1000 ohm RTD or platinum resistance thermometer. Figure 4 shows a typical RTD configuration.

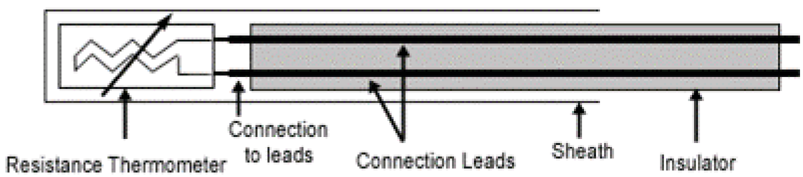

Figure 4: Typical RTD configuration.

For evaluating the output signal a constant current is passed through the resistance and the voltage drop across it is measured. This voltage drop follows Ohm's Law, V = I R.

The measuring current should be selected to be as small as possible in order to avoid heating of the sensor. It can be assumed that a measuring current of 1 mA does not introduce any appreciable error. This current produces a voltage drop of 0.1 V in a Pt 100 at 0°C. This signal voltage must now be transmitted through the connecting cables to the indicating or evaluation point with a minimum of alteration. There are three different types of connecting circuit:

- 2-wire circuit: the connection between the thermometer and the evaluation electronics is made with a 2 conductor cable (Figure 5 left). Like any other electrical conductor this cable has an electrical resistance which is placed in series with the resistance

thermometer. The two resistances are therefore added together which is interpreted by the electronics as an increased temperature. With longer distances the line resistance may amount to a few Ohms and produces an appreciable shift in the measured value.
This problem can be avoided without the use of a multiconductor cable by employing a 2-wire transmitter. The transmitter converts the sensor signal into a normalized current signal of 4 - 20 mA which is proportional to temperature. The supply to the transmitter is also run through the same two connections, using a base current of 4 mA. The 2-wire transmitter offers the additional advantage that the amplification of the signal greatly reduces the effects of external interference. There are two arrangements for positioning the transmitter. Since the distance for the unamplified signal should be kept as short as possible the amplifier can be mounted directly on the thermometer inside its terminal head. This optimum solution is some times impossible for constructional reasons or the consideration that the transmitter may be difficult to reach in case of a fault. In such situations a rail mount transmitter is mounted inside the control cabinet. The advantage of improved access is bought at the expense of the longer distance over which the unamplified signal has to travel.

- 3-wire circuit: in order to minimize the effects of the line resistances and their fluctuation with temperature it is usual practice to employ a three-wire circuit. It consists of running an additional wire to one contact of the RTD. This results in two measuring circuits of which one is used as reference. The 3-wire circuit (Figure 5 center) makes it possible to compensate for the line resistance both in its amount and in its temperature variation. It is however a requirement that all three conductors have identical properties and are exposed to identical temperatures. This usually applies to a sufficient degree so that the 3-wire circuit is the most widely used method today. No line balancing is required.

- 4-wire circuit: the optimum form of connection for resistance thermometers is the 4-wire circuit (Figure 5 right). The measurement depends neither on the line resistances nor on their variations due to temperature. No line balancing is required. The thermometer is supplied with the measuring current through the supply connections. The voltage drop across the measurement resistance is picked off by the measurement lines. If the input resistance of the electronics is many times greater than the line resistance, the latter can be neglected. The voltage drop determined in this way is then independent of the properties of the connecting wires. This technique is usually used in scientific apparatus requiring accuracies measured in hundredths of a degree.

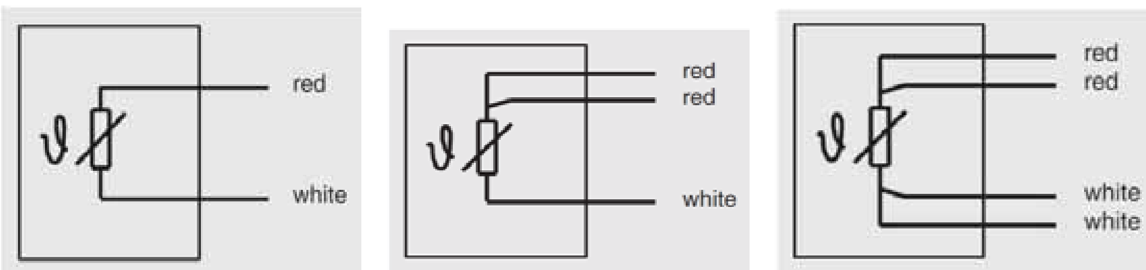

Figure 5: Different RTD wire circuits: 2-wire (left), 3-wire (center) and 4-wire (right)

Thermistors are based on resistance change in a ceramic semiconductor; the resistance drops nonlinearly with temperature rise. Because the resistance characteristic falls off with increasing temperature they are called negative temperature coefficient (NTC) sensors. Their typical appearance is shown in Figure 6.

Figure 6: Typical thermistors.

The resistance of thermistors is normally several orders of magnitude greater than any lead resistance. The lead resistance therefore has a negligible effect on the temperature reading and thermistors are almost always connected in a 2-wire configuration.

Accuracy and range of application.
The accuracy of the thermocouples is determined by (DIN) 43710. It is slightly poorer than for the other sensors (on the average +0.75% of the measurement range). For temperatures up to 400 °C, the DIN-permitted deviation is 3°C. Thermocouples with an accuracy of 1/2 or 1/4 of the permissible DIN deviation (e.g., a maximum deviation of 1.5 °C or 0.75 °C, respectively) are commonly used.

Standard tables show the voltage produced by thermocouples at any given temperature, so for example in the diagram of Figure 3, the K type thermocouple at 300°C will produce 12.2mV. Unfortunately it is not possible to simply connect up a voltmeter to the thermocouple to measure this voltage, because the connection of the voltmeter leads will make a second, undesired thermocouple junction. To make accurate measurements, this must be compensated for by using a technique known as cold junction compensation (CJC).

As already described, RTDs consist of an encapsulated metallic wire (usually platinum) with two to four connector wires. As the four-wire configuration allows for the compensation of the wire resistance, this configuration is preferred and is highly recommended. The measuring accuracy, as regulated by IEC 751, is ±0.3K at 0°C, ±0.8K at 100°C, and ±1.55K at 250°C. These are the most accurate sensors for industrial applications and also offer the best long-term stability. A representative value for the accuracy of a platinum resistance is +0.5 percent of the measured temperature. After one year there may be a shift of +0.05°C through aging. Platinum resistance thermometers can cover temperature ranges from -200 to 800°C.

The resistance/temperature curve for a 100Ω platinum RTD, commonly referred to as Pt100, is shown in Figure 7. This relationship appears relatively linear, but curve fitting is often the most accurate way to make an accurate temperature measurement.

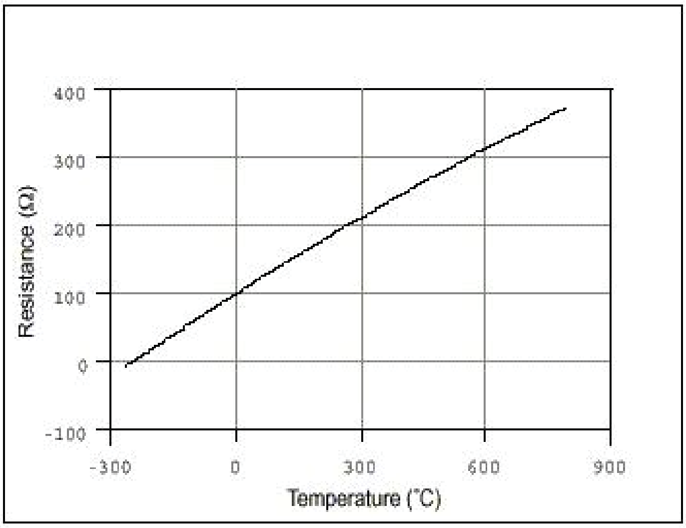

Figure 7: Typical resistance-temperature curve.

RTD's are more accurate than thermocouples but their temperature range is not as broad: thermocouples offer the clear advantage of a higher upper temperature limit, up to several thousand degrees Celsius. Besides, thermocouples response is faster than RTDs.

Thermistors have a more restrictive span, as due to the nature of the basic process in which are based, the number of conducting electrons increases exponentially with temperature; the characteristic curve therefore exhibits a strongly rising form. This pronounced non-linearity is a disadvantage of NTC resistors and limits their useful temperature span to about 100°C. They can of course be linearised by an automation computer. However, accuracy and linearity generally do not meet the requirements over larger measurement spans.

Thermistors and RTD's share another very important limitation: selfheating, which can be significant when dealing with a still fluid.

Long term performance and reliability.
A general conclusion from the reviewed experiences, as the partial dismantling of the FEBEX experiment [13], is that temperature sensors sustain the harsh conditions in maturing buffer and backfill, including high pressure and strain. However, their sensitivity to chemical attack by the pore water may cause quick breakdown and special metals or metal coatings, etc, should be considered for application in demanding chemical environments.

By detailed calibration of thermocouples, accuracy similar to RTD's can be obtained. However, longterm stability of RTD's is better than for thermocouples, which is somewhat poor. The drift of thermistors under alternating temperatures is also larger than for RTD's. Their field of use is limited to monitoring and indicating applications where the temperatures do not exceed 100°C. In such simple applications they are actually preferable to more expensive thermocouples and RTD's in view of their low cost and the comparatively simple electronic circuitry required. In addition they can be produced in very small designs with a fast response and low thermal mass.

Particularities
Use of long metallic sheaths of high quality (304, 321 or 316 SS or Inconel 600…) plus MgO insulation is common for thermocouples. It is also possible for RTDs, but sheath diameter is higher and therefore they are more rigid.

One of the main advantages of thermocouples is that long cables can be used without need for compensation of the line resistance by means of three or four wires circuits, as in the case of RTD's.

Data acquisition units
Recording of the temperature evolution is well demonstrated using corrosion-protected temperature sensors and advanced data acquisition systems, such as in the FEBEX experiment [13] or the Mont Terri HE-B experiment [14].

Conclusions
Some conclusions can be extracted:

- Platinum RTD's are the most accurate and stable sensors over a long time period. Their cost is typically higher than for thermistors and thermocouples.
- Thermistors are not quite as accurate or stable as RTD's but they are easier to wire, and cost slightly less. Note though that thermistors are available in many different base resistances and with many different curves. The right thermistor must be specified for each case.
- Thermocouples are widely used in industrial applications because they work reliably at very high temperatures and are less expensive than RTD's. They are seldom used within temperature ranges less than 100°C. They are, however, used frequently in flue gas measurements in conjunction with 2-wire transmitters. They can be wired over long distances.
- Platinum RTD's are often preferred in industrial applications because of their improved accuracy and long term stability. The latter would be the main argument when thinking about an application within final repositories.

Finally, Table 1 gives a qualitative comparison of the three temperature sensing technologies:

Table 1: Temperature measurement devices comparison chart

Criteria	**Thermocouple**	**RTD**	**Thermistor**
Temp Range	-270°C to 2300°C	-240°C to 650°C	-100°C to 500°C
Accuracy	Good	Best	Good
Linearity	Better	Best	Good
Sensitivity	Good	Better	Best
Cost	Best	Good	Better
Long-term stability	Good	Best	Poor

Context of application within Repository Monitoring
Temperature is one of the key parameters to assess the THM evolution of a repository. Differences in temperature in a repository come basically from the radioactive decay of the spent fuel. Therefore, the zones of thermal influence around the canisters of spent fuel are the natural targets for temperature measurements, so to obtain temperature gradients within the engineered and natural barriers, and to monitor the changes of temperature profiles along time.

References of use in previous experiences
Practically all the experiences of simulation of deep storage repositories throughout the different underground research laboratories comprise temperature measurements, especially when they

feature heating elements to simulate the decay heating of the spent fuel. Some of such experiences sorted by underground laboratories follow:

- Grimsel Test Site (Switzerland):
    - FEBEX [15]
- Mont Terri Laboratory (Switzerland):
    - Heating Experiment [16]
    - Heating Experiment-E [17]
- Äspö Hard Rock Laboratory (Sweden):
    - Prototype Repository [18]
    - Temperature Buffer Test [19]
- Bure Research Laboratory (France):
    - TER
    - TED

Limitations
The range of temperatures in a future repository is well below the operating range of the sensors considered, so no limitation can be considered in this sense.

The main limitations are those affecting the sensors integrity from a mechanical and chemical point of view, which can reduce the expected lifetime of the sensors.

Besides, temperature sensors located in the vicinity of the canisters could be affected by radiation.

Further developments
This is a well known technology, so no specific improvements can be envisaged.

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3.1.1.2 Mechanical pressure

Why measure mechanical pressure?
Mechanical pressure is another key parameter in the THM behaviour of a repository. It provides a direct view of the development of bentonite swelling and hence of its sealing capacity, which is one of the essential issues to be addressed within a repository.

Techniques and signal characteristics
Different types of sensors based on various techniques have been developed to measure mechanical pressure. The most commonly used are strain gauges, piezoelectric sensors, capacitive sensors, resonant wire sensors and optical sensors.

Strain gages measure by means of a Wheatstone bridge arrangement the change in resistance of a metal wire as it is elastically deformed by pressure. This deformation is not permanent if the pressure (applied force) does not exceed the elastic limit of the metal. If the elastic limit is exceeded then permanent deformation will occur.

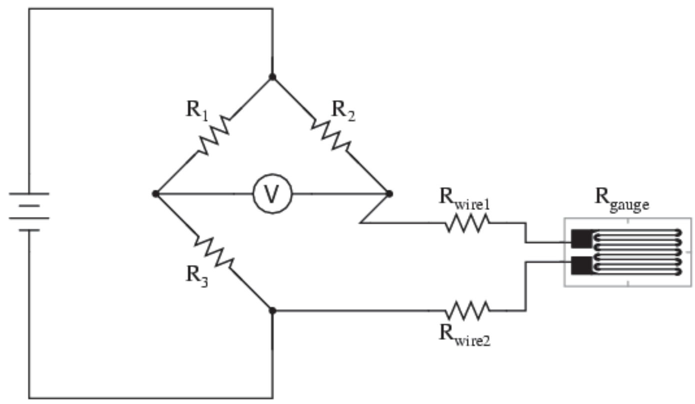

Figure 8: Strain gauge with Wheatstone bridge.

The change in pressure is detected as a change in the measured voltage: when the process pressure is applied to the sensor, this creates a small deflection of the sensing diaphragm, which applies strain to the Wheatstone bridge circuit within the sensor. The change in resistance is sensed and converted to a digital signal for processing by the microprocessor.

The gauges are placed directly on the diaphragm, or on a secondary element that is deformed by the diaphragm through a mechanical link. Secondary elements are conceived to provide a certain amplifying effect of the deformation, as well as to favour the thermal balance. Some utilised elements are single or double cantilevers, probe rings and deformation tubes. In the latter, two gauges are placed, one to measure longitudinal deformation connected in series with the other, placed perpendicularly to measure transversal deformation. This does not result in an increase of sensitivity, but allows the compensation of thermal effects.

Piezoelectric sensors measure the instantaneous electric charge generated by a crystal when deformed, being this charge proportional to the applied force causing the deformation (piezoelectric effect). Hence theses are force probes, so they require a primary sensor to transform the pressure into force, generally a diaphragm.

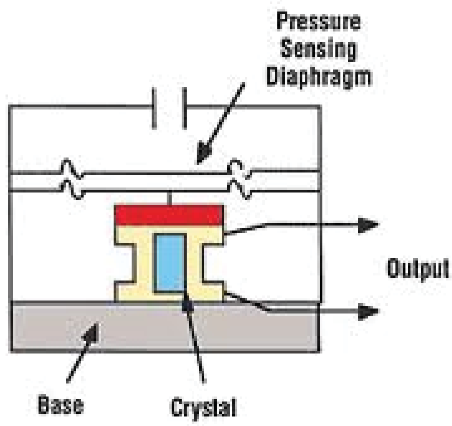

Figure 9: Piezoelectric pressure transducer.

The effect appears when crystalline structures are deformed along some given characteristic directions, which produce non-compensated electric charges in two different faces of the crystal.

There are two different effects: longitudinal, and transversal:

- In the longitudinal effect, the charges appear in the faces where the force is applied, with values depending only on the force applied, independently of the crystal size. Therefore, in order to increase the sensor sensitivity several crystal disks piled together are used, adding up their charges. Gaps between disks can produce loss of linearity of the sensor using this array.
- In the transversal piezoelectric effect, charges appear in faces perpendicular to the face where the force is applied, and their magnitude depend both on the amount of force applied and on the crystal dimensions. Hence, it is possible to obtain sensors with different sensitivities, adequate to different measuring ranges by choosing the appropriate crystal and diaphragm size.

Although quartz provides less electric charge than other piezoelectric materials, it has been broadly used due to its characteristics, namely: resistance to very high pressures in the order of 40 000 bar, although the practical maximum value is lower, limited by the quality of the crystal-electrode joints; high working temperature, up to 500 ºC, although over 200 ºC (Curie's point) their crystalline structure undergoes transformations that produce a partially irreversible loss of piezoelectric characteristic; small sensitivity of piezoelectric coefficient to temperature (-0.02 to -0.05 % f.s. per ºC) if below the Curie's point; high insulation resistance through the crystal itself, which makes more difficult the inner compensation of charges; high linearity and lack of hysteresis.

Initially, natural quartz crystals were used for these sensors, but the use of artificial crystals was introduced progressively as they had no impurities.

Capacitive sensors measure the change in capacitance between two capacitor plates, powered by a high frequency oscillator, when one of them moves due to the pressure applied to the sensing diaphragm to which is attached.

Two main arrangements can be considered: cylindrical and flat capacitor. The cylindrical ones measure displacement and they are quite linear (less than 0.1 % f.s.) as the effective surface of the capacitor changes linearly with displacement. The flat ones can be assumed linear if the variation of distance between plates is small with regard to the distance without load and none of them is rigid. If one of the plates is rigid and the other is a deformable diaphragm, the transducer is non-linear, but the error is linear and can be calculated easily. For measuring differential pressure another arrangement is used with the diaphragm placed between two rigid plates. In this case, temperature error is self-compensated.

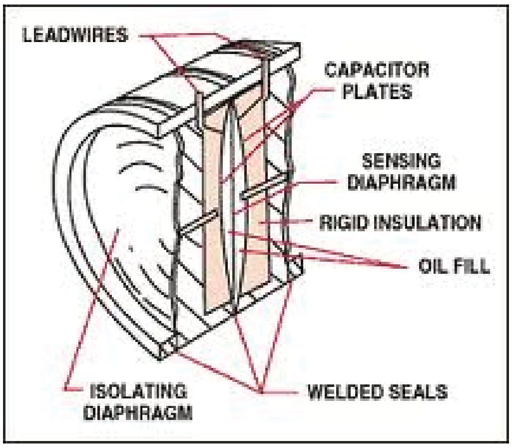

Figure 10: Capacitive pressure transducer with flat capacitor.

Vibrating wire sensors measure the change in natural frequency of a wire under tension, which is caused to vibrate by an electronic oscillator circuit, when that tension changes due to the pressure applied to the diaphragm where the wire is located. More extended information can be found in Section 3.1.1.4.

Optical sensors, finally, measure by means of a measuring diode the disturbance to an infrared light beam emitted by a LED when partially blocked by an opaque plate. The plate blocks the light when it is displaced due to the pressure applied to the sensing diaphragm on which is mounted.

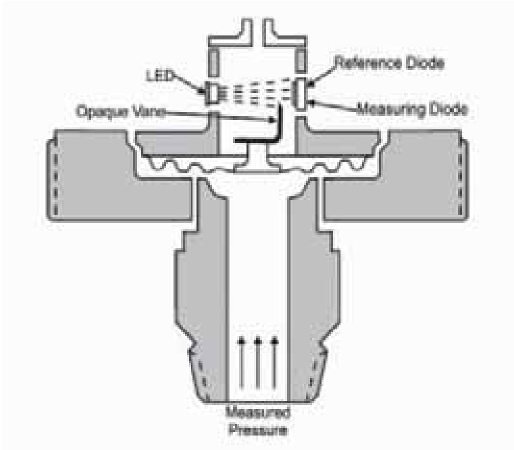

Figure 11: Optical pressure sensor.

A reference diode is used to compensate for the ageing of the light source. Besides, the use of a reference diode cancels the thermal effect out as temperature affects both the reference and the sensing diodes in the same way.

Accuracy
For strain gauges, piezoelectric and capacitive sensors a similar accuracy around 0.1 % f.s. is considered, while for resonant wire is 0.2 % f.s. and for optical sensors is 0.5 % f.s.

In general all of them are temperature sensitive and need compensation, except for the optical ones, but in strain gauges it can be done internally, as the sensor is self compensated. Strain gauges are more likely to have hysteresis due to thermoelastic strain while vibrating wire sensors are non-linear.

Long term performance and reliability
Strain gauges are stable devices with no moving parts. Capacitive and Piezoelectric sensors are robust too, not afected by vibrations, and have no frictions inside. Optical sensors comprise moving parts, which make them more fragile. Although sensitive to shocks or vibrations, vibrating wire sensors are quite robust and stable in the long term, and therefore they have been the preferred choice in experiments as ESDRED [20] and FEBEX [21] in the Grimsel laboratory. In the latter they have proved to be a reliable option in the long term and, in comparison, capacitive sensors installed in the same experiment have registered a higher failure rate in a shorter time. In particular, for these sensors special care must be taken at the cable inlet to the case housing the sensing element, as failing to obtain water tightness at this point can lead to a massive failure of the instrumentation. This was the case in the HE-B experiment in Mont Terri.

Installation
Vibrating wire sensors tend to be large in size, which can be a drawback in applications where space is restricted, or where a minimal disturbance to the barrier is desired. On the contrary, strain gauges and piezometric sensors are small in size, and the size of capacitive sensors is reasonable too.

Particularities
Piezoelectric sensors take dynamic measures, which means they can measure for a short period of time when a pressure change occurs. Therefore, they are not recommended for applications where static pressure measure is required, which is often the case in repositories.

In terms of cost, capacitive and optical sensors use to be the most expensive ones.

Data acquisition units
Capacitive sensors provide a fast response directly in volts, and as they are quite linear the conversion is direct. Piezoelectric sensors provide a self-generated signal too. Strain gauges provide low level signals. Vibrating wire sensors require dedicated data acquisition units to convert the signal to digits, and still another conversion is required to convert them to pressure units. Optical sensors require conversion too.

Conclusions
Many different techniques are available to perform accurate measures of mechanical pressure, and most of them are sufficiently good. Choosing one or another depends on the particularities of each application, but in principle vibrating wire sensors have proved to be robust and reliable over long periods of time, so they are a good choice for a nuclear repository where sensors lifetime can be a key issue. Some of their characteristics, as the large size of sensors, should not be an impediment in a large facility as a nuclear repository, but some others can be critical to discard these sensors, as their compatibility with the potential use of wireless data transmission techniques. As these sensors need signal conditioning, in the case of wireless transmission the signal must be conditioned before the data transmission. This means burying bulky and delicate signal conditioning electronics close to the sensor, with the additional problems of high battery power consumption and inaccessibility for maintenance and repair. In those cases, a sensor providing a direct signal is a better choice.

Context of application within Repository Monitoring
The main use of these sensors lies on the monitoring of swelling pressure. Therefore, they are normally limited to barriers of the repository with swelling materials. These can be both engineered barriers, as the buffer and backfill containing bentonite in different percentages, and natural barriers, as clayish host rocks like argillite.

They are normally placed in different orientations to measure the mechanical pressure in different directions, as radial axial and tangential in galleries, or in perpendicular directions within boreholes.

They are placed too in interfaces between different components of the repository, as in the contact between the buffer and sealing plugs.

References of use in previous experiences
Practically all the experiments in underground research laboratories incorporate this type of sensors, see for instance the references corresponding to FEBEX [15] & GAST [22] at GTS, BPT [23] & Prototype [24] at HRL or EB [25] at MTL.

Limitations
No limitations can be considered in terms of measuring range, as these sensors can measure the pressures normally expected within a repository, in the order of 5 MPa to 10 MPa,

One of the drawbacks of total pressure sensors is their large size in some cases, which supposes an additional difficulty in terms of installation and level of intrusion within the barriers.

Further developments
One of the developments still to be addressed for this type of sensors is the reduction of size without compromising the mechanical strength.

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3.1.1.3 Water content & Humidity

Why measure water content and humidity?
Along with temperature and pressure, this is the third key parameter in the THM evolution of a repository. The degree of saturation of the engineered barrier is directly linked with its performance over time. Hence the importance of its monitoring.

Concepts and definitions
In a very simplified manner, the construction of a Nuclear Waste Repository involves the excavation of a rock and the later emplacement of the waste in the voids, where it is isolated thanks to the engineered barrier system. Such process implies some degree of rock desaturation (due to the un-confinement and the ventilation) and the emplacement of buffer material and/or the backfill, as well as components of the seals, which are not fully saturated. With time the rock and the remaining repository components will become saturated.

At the early stage, the main components of the repository are partially saturated, which means that they contain void spaces (pores) which are partially filled with liquid (water) and partially with gas. The ratio of the volume of pores to the total volume of the solid is the porosity. The term saturation or degree of saturation relates to the amount of water contained in the pores.

In this sense the water content of a sample can be expressed as mass (or gravimetric) water content (ratio of the mass of water to the sample mass) or as volumetric water content (ratio of the volume of water to the sample volume). The term humidity describes the quantity of water vapour in a gas volume.

Alternative and also appropriate measurements for unsaturated conditions are water potential and total suction. Water potential is the potential energy of water per unit volume relative to pure water in reference conditions. Water potential quantifies the tendency of water to move from one area to another due to osmosis, gravity, mechanical pressure, or matrix effects such as surface tension.

Total suction is defined in terms of the free energy or the relative vapour pressure (relative humidity) of the solid moisture. The total suction is correlated with the relative humidity by Kelvin's law. The retention curve of a material correlates the degree of saturation with the total suction.

Although volumetric water content is a more intuitive quantity, water is strongly retained by several materials (soils, clays ...); for instance, by the buffer or the backfill. Therefore, total suction may be a more useful measurement since it is a measure of the energy that must be invested to extract water. This is especially interesting for modelling purposes.

Techniques and signal characteristics

Water content can be directly determined only using the difference in weight before and after drying a sample (gravimetric method) but obviously this can not be done for monitoring the Repository. Alternatively, many indirect methods are available to monitor water content; these methods estimate water content by a calibrated relationship with some other measured variable. The suitability of each method depends on cost, accuracy, response time, installation, intended use, management, and durability.

Depending on the measured property, indirect techniques are classified into volumetric or tensiometric methods. While the former gives volumetric water content, the latter yields total suction or water potential.

1. Neutron Moderation

Fast neutrons are emitted from a decaying radioactive source ($^{241}Am/^{9}Be$). When they collide with particles with the same mass as a neutron (i.e. protons, H^{+}), they slow down dramatically, building a "cloud" of "thermalized" (slowed) neutrons. Since water is the main source of hydrogen (in soils and similar materials), the density of slowed neutrons formed around the probe is proportional to the volume fraction of water present.

The probe can be configured for insertion or surface measurement. Insertion probe is a long and narrow cylinder containing a source and a detector. Measurements are made by inserting the probe into an access tube that is installed in the measured material. Moisture can be determined at various depths by placing the probe at different depths in the tube. There are probes to remain inserted in the material and surface probes, both usually applied to silos of bulk material.

Figure 12: Neutron moderation: equipment: probe versions and readout

Water content is obtained from a linear calibration between the count rate of slowed neutrons read by the probe in the field and the moisture content obtained from nearby field samples.

Advantages:

- Robust and accurate (±0.5%).
- Inexpensive per location (i.e. a large number of measurements can be made at different points with the same instrument).
- One probe can measure many different depths.
- Large soil sensing volume (sphere of influence with 10 – 40 cm radius, depending on moisture content).
- Not affected by salinity or air gaps.
- Stable specific calibration.
- Quick response time: 1-2 minutes.

Drawbacks:

- Safety hazard, since a radioactive source is involved. (Even at 40 cm depth, radiation losses through soil surface have been detected.)
- Requires certification to use it.
- Requires specific calibration.
- Heavy, cumbersome instrument.
- Takes a relatively long time for each reading.
- Readings close to the soil surface are difficult and inaccurate.
- Manual readings only; cannot be automated due to safety hazard.
- Expensive.
- Sphere of influence may vary for the following reasons:
  a) It increases as the soil dries, due to presence of fewer hydrogen atoms. The probability of collision is smaller, so fast neutrons travel further from the source.
  b) It is smaller in fine-textured soils. Since these soils hold more water, the probability of collision closer to the source becomes higher.
  c) If there are layers with large differences in water content due to changes in soil physical properties, the sphere of influence can have a distorted shape.

- Materials with high organic matter contents require specific attention and specialized calibration because organic compounds contain significant amounts of hydrogen.

Radiation hazard precludes semipermanent installation and hence automation, and acquisition, transport, use, storage and eventual disposal of a neutron probe is subject to strict regulation because of the potential hazard to human health and the environment. Nowadays, the neutron method tends to be replaced by dielectric methods.

2. Volumetric methods: Dielectric techniques.

They estimate water content by measuring the bulk permittivity (or dielectric constant) of the medium, which determines the velocity of an electromagnetic wave or pulse through the material being measured. In a composite material, air and water permittivity is determined by the relative contribution of each of the components. Since the dielectric constant of liquid water is much larger than that of the other constituents, the total bulk permittivity is governed primarily by the presence of liquid water. The relationship between the permittivity and the water content depends on the electromagnetic wave frequency sent by the specific monitoring device and usually requires a specific calibration. The dielectric methods described below use empirically-calibrated relationships between volumetric water content and the sensor output signal (time, frequency, impedance, wave phase). These techniques are becoming widely adopted because measurements are almost instantaneous, the instruments require minimal maintenance, and they can provide continuous readings through automation.

- *Time Domain Reflectometry (TDR)*

The soil bulk dielectric constant (Ka_b) is determined by measuring the time it takes for an electromagnetic pulse (wave) to propagate along a transmission line (TL) that is surrounded by the material to be measured. Since the propagation velocity (v) is a function of Ka_b, the latter is proportional to the square of the transit time (t, in seconds) out and back along the TL:

$$Ka_b = (c/v)^2 = [(c \times t)/(2 \times L)]^2 \quad (2),$$

where c is the velocity of electromagnetic waves in a vacuum and L is the length of the TL embedded in the material.

A TDR instrument requires a device that produces a series of precisely timed electrical pulses across a wide range of high frequencies (e.g. 0.02 - 3 GHz), which travel along a TL comprised of a coaxial cable and a probe. This high frequency provides a response that is less dependent on material specific properties like texture, salinity or temperature. The TDR probe usually consists of 2 - 3 parallel metal rods that are inserted into the material and act as waveguides in a similar way as an antenna is used for television reception. At the same time, the TDR instrument uses a device to measure and digitize the energy (voltage) of the TL at intervals down to around 100 picoseconds. When the electromagnetic pulse travelling along the TL finds a discontinuity (e.g. probe-waveguides surrounded by material), part of the pulse is reflected, producing a change in the energy level of the TL. The travel time (t) is determined by analyzing the digitized energy levels.

Figure 13: Time domain reflectometry (TDR) equipment: probe versions and readouts.

Salinity and/or highly conductive heavy clays may affect TDR measurements, since each contributes to attenuation of the reflected pulses. In other words, TDR is relatively insensitive to salinity as long as a useful pulse is reflected (i.e. as long as it can be analyzed). In highly saline materials, using epoxy-coated probe rods may solve the problem. However, this implies loss of sensitivity and change in calibration. In addition to time of travel, other characteristics of the pulse travelling through the material (e.g. change in size or attenuation) can also be related to its electrical conductivity. Pulse attenuation has been used in some commercial devices to measure water content and electrical conductivity simultaneously.

Advantages:
- Accurate (±1%).
- Easily expanded by multiplexing.
- Wide variety of probe configurations (various sensing depths).
- Minimal disturbance.
- Relatively insensitive to normal salinity.
- Can provide simultaneous measurements of electrical conductivity.

Drawbacks:
- Relatively expensive equipment due to complex electronics.
- Potentially limited applicability under highly saline conditions or in highly conductive heavy clay soils.
- Specific calibration required for materials having large amounts of bound water (e.g. those with high organic matter content, volcanic soils, etc.)
- Relatively small sensing volume (about 30 mm radius around length of waveguides).

- *Frequency Domain (FD): Capacitance and FDR*

The electrical capacitance of a capacitor that uses the measured material as a dielectric depends on water content. When this capacitor (made of metal plates or rods imbedded in the material or in access tubes) is connected to an oscillator to form an electrical circuit, changes in moisture can be detected by changes in the circuit operating frequency. These changes form the basis of the Frequency Domain (FD) technique used in Capacitance and Frequency Domain Reflectometry (FDR) sensors. In capacitance sensors, a medium's dielectric permittivity is determined by measuring the charge time of a capacitor made with that medium. In FDR, the oscillator frequency is controlled within a certain range to determine the resonant frequency (at which the amplitude is greatest), which is a measure of water content in the material.

Probes usually consist of two or more electrodes (e.g. plates, rods, or metal rings around a cylinder) that are inserted into the measured specimen (see Figure 14). With the ring configuration, the probe is introduced into an access tube installed in the field. When an electrical field is applied, the material around the electrodes (or around the tube) forms the dielectric of the capacitor to complete the oscillating circuit. In some cases, an access tube is used to allow multiple sensors to measure moisture at different depths.

Figure 14: Frequency domain (FD) probes: a) capacitance (plates embedded in a silicon board); b) capacitance (rods); and c) FDR (rings).

A specific calibration is recommended because the operating frequency of these devices is generally below 100 MHz. At these low frequencies the bulk permittivity of minerals may vary and the estimation is more affected by temperature, salinity, bulk density and clay content.

Advantages:

- Accurate after specific calibration (±1%)
- Can be used with high salinity where TDR fails.
- Better resolution than TDR (avoids the noise that is implied in the waveform analysis performed by TDRs).
- Can be connected to conventional data loggers (DC output signal).
- More flexibility in probe design (measurements can be made at different depths at the same location compared with TDR that usually measures at a specific depth).
- Some devices are relatively inexpensive compared with TDR due to use of low frequency standard circuitry.

Drawbacks:

- The sensing sphere of influence is relatively small (about 40 mm).
- For reliable measurements, it is critical to have a good contact between the sensor (or access tube) and the material. Careful installation is necessary to avoid air gaps.
- Tends to have larger sensitivity to temperature, bulk density, clay content and air gaps than TDR.
- Needs specific calibration.

- *Amplitude Domain Reflectometry (ADR): Impedance*

When an electromagnetic wave (energy) travelling along a transmission line (TL) reaches a section with different impedance (that has two components: electrical conductivity and dielectric constant), part of the transmitted energy is reflected back to the transmitter. The reflected wave interacts with the incident wave producing a voltage standing wave along the TL, i.e. change of wave amplitude along the length of the TL. If the material/probe combination causes the impedance change in the TL, measuring the amplitude difference will give the impedance of the probe -Gaskin and Miller (1996) [26]; Nakashima et al., (1998) [27]-. The influence of the electrical conductivity of the material is minimized by choosing a signal frequency so the water content can be estimated from the material/probe impedance.

Impedance sensors use an oscillator to generate a sinusoidal signal (electromagnetic wave at a fixed frequency, e.g. 100 MHz) that is applied to a coaxial TL. The TL extends into the material through an array of parallel metal rods, the outer of which forms an electrical shield around the central signal rod (see Figure 15).

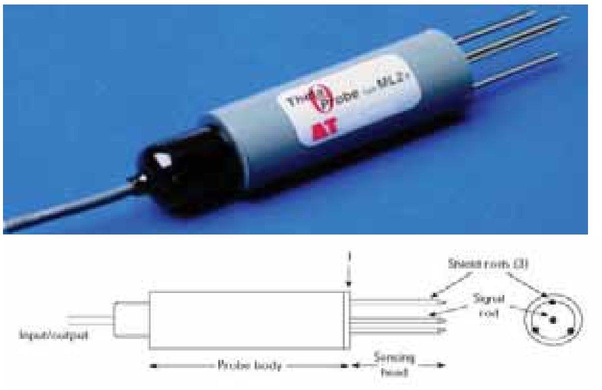

Figure 15: Amplitude domain reflectometry (ADR) probe

This rod arrangement acts as an additional section of the TL, having impedance that depends on the dielectric constant of the material between the rods. Measuring range: 5-55%, accuracy: 5%, resolution: 1%.

Advantages:

- Accurate to within ±1% with specific calibration and ±5% without calibrating.
- Allows measurements in saline conditions up to 20 dS/m.
- Minimal disturbance.
- Can be connected to conventional data loggers (DC output signal).
- Inexpensive due to standard circuitry.
- Not affected by temperature.
- In-situ estimation of bulk density possible -Wijaya et al., (2002) [28].

Drawbacks:

- Specific calibration recommended for reliable measurements.
- Measurement affected by air gaps, stones or channelling water directly onto the probe rods.
- Small sensing volume (0.27 in^3).
- Could have hysteresis.

- *Phase Transmission*

After travelling a fixed distance, a sinusoidal wave shows a phase shift relative to the phase at the origin. This phase shift depends on the length of travel along the TL, the frequency, and the velocity of propagation. Since propagation velocity is related to material moisture content, water content can be determined by the phase shift for a given frequency and length of travel.

The probe uses a particular waveguide design (two open concentric metal rings) so that phase measuring electronics can be applied at the beginning and end of the waveguides (see Figure 16).

Figure 16: Phase transmission probe and sensor

Advantages:

- Accurate with specific calibration (±1%).
- Large sensing volume (110 – 135 dm^3).
- Can be connected to conventional data loggers (DC output signal).
- Inexpensive.

Drawbacks:

- Considerable disturbance during installation due to concentric rings sensor configuration.
- Requires specific calibration.
- Sensitive to salinity levels >3 dS/m.
- Reduced precision due to distortion of pulse during transmission.

- *Time Domain Transmission (TDT)*

This method measures the time for an electromagnetic pulse to propagate one-way along a transmission line (TL). Thus, it is similar to TDR but requires an electrical connection at the beginning and end of the TL. Notwithstanding, the circuit is simple compared with TDR instruments.

The probe has a waveguide design (bent metal rods) so that the beginning and end of the transmission line are inserted into the electronic block. Alternatively, the sensor consists of a long band (~1 m) with an electronic block at both ends (see Figure 17).

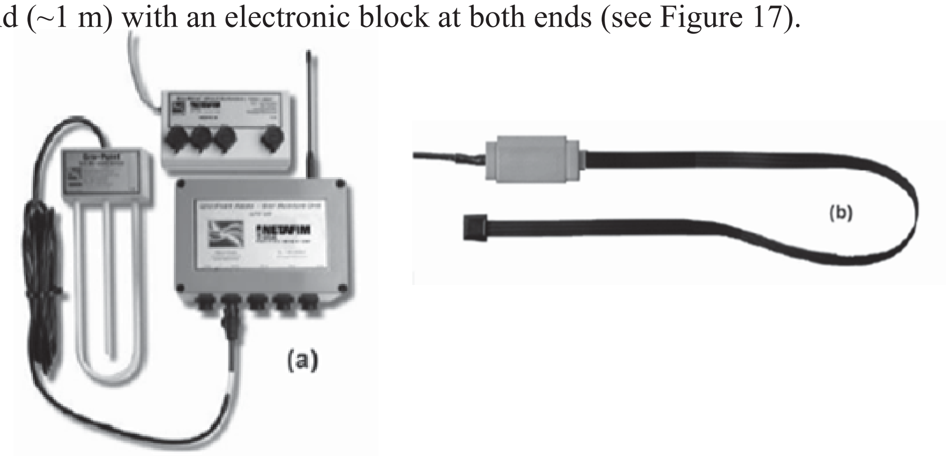

Figure 17: Time domain transmission (TDT) probe.

Advantages:

- Accurate (±1 – 2%).
- Large sensing volume (0.5 – 7 dm^3).
- Can be connected to conventional data loggers (DC output signal).
- Inexpensive due to standard circuitry.

Drawbacks:

- Reduced precision due to distortion of the generated pulse during transmission.
- Disturbance during installation.

3. Tensiometric Field Methods

The instruments used for measuring pore water pressures are called piezometers. Where piezometers have been specifically designed for measuring water stress states that are below the prevailing atmospheric pressure condition the devices have been given the specific name of tensiometers.

Tensiometric methods estimate the water matric potential, which includes both adsorption and capillary effects. The matric potential is one component of the total water potential that also includes gravitational (position with respect to a reference elevation), osmotic (salts in solution), and gas pressure (from entrapped air). The sum of matric and gravitational potentials is the main driving force for water movement.

All tensiometric instruments have some type of porous interface in contact with the material to measure through which water can move. In a dry material, water is drawn out of the porous interface, while in a wet one water moves from the material into the interface. In general, tensiometers do not need a specific calibration, but before reading sufficient time must be allowed after field installation so the device and the material can equilibrate.

- *Tensiometer*

A sealed, water-filled tube is placed in contact with the soil through a permeable and saturated porous material, and the water inside the tube comes into equilibrium with the soil solution (i.e. it is at the same pressure potential as the water held in the soil matrix). Hence, the soil water matrix potential equals the vacuum or suction created inside the tube.

Tensiometers consist of a sealed water-filled plastic tube with a ceramic cup at one end and a negative pressure gauge (vacuometer) at the other (see Figure 18). The shape and size of the ceramic cup can be variable and the accuracy depends on the gauge or transducer used (about 1 centibar). Typically the measurement range is 0 - 80 centibars.

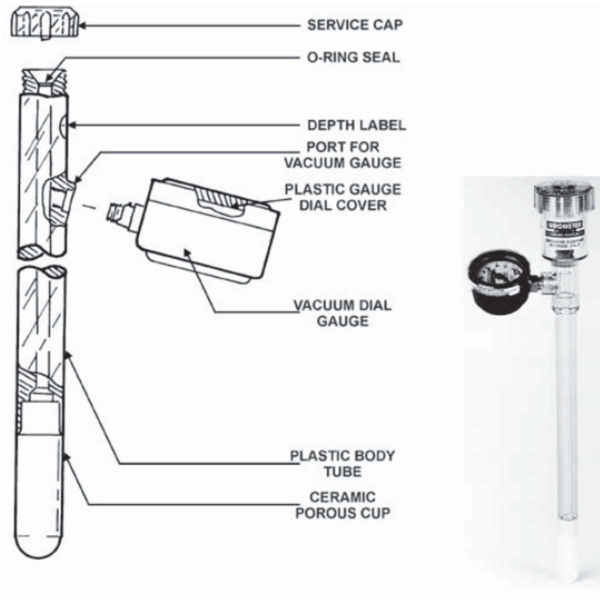

Figure 18: Example of a manual tensiometer

With time the range of measurements was maximised by placing the pressure sensor at the same depth as the porous filter. Nowadays there are miniature tensiometers specially designed for punctual measurements, with an active surface of only 0,5 cm^2 and a diameter of 5 mm the ceramic tip has all advantages of small dimensions: little soil disturbance, punctual pick-up and fast response (see Figure 19). There are special versions tested to reach a measuring range of -160 kPa or even go down to -250 kPa before running empty, sometimes even to -450 kPa, but this is an exception and cannot be guaranteed.

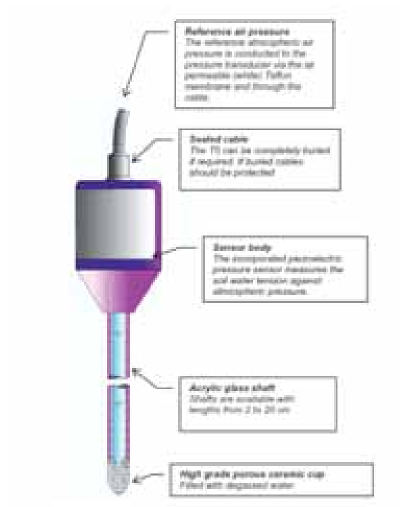

Figure 19: Miniature tensiometer

Ridley et al. (2003) [29] introduced a refinement of the Bishop ‘‘twin-tube’’ piezometer in which the pressure sensor is located adjacent to the porous filter and in which the tubes used to remove air from the piezometer and introduce fresh de-aired water can be isolated by a valve close to the filter and the sensor, thereby maximising the range of measurements irrespective of the depth to which the filter and the sensor are installed (see Figure 20). The same concept is available in recent tensiometers.

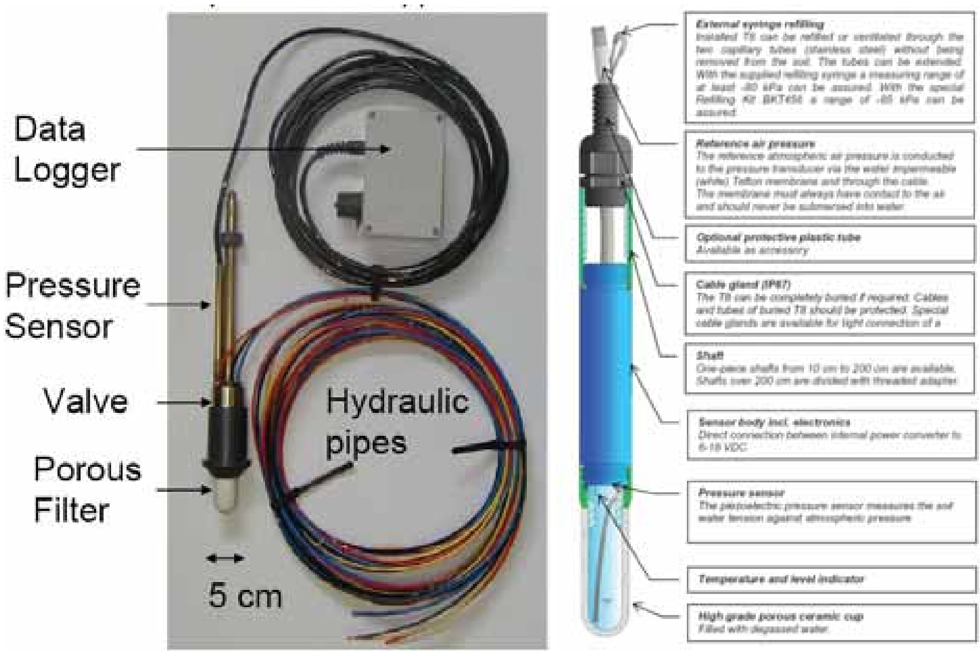

Figure 20: Twin-tube tensiometers

Furthermore, there are modern tensiometers that integrate a bidirectional miniature pump between pressure transducer and ceramic cup (see Figure 21). A microcontroller controls the functions of pump and sensors. To refill the cup, a negative pressure, lower than the actual water tension in the surrounding material, is established to draw water into the ceramic cup. Excess water is released through an exhaust back into the material but in a special version can be equipped with an additional outlet tube. Then, the excess water is not discharged through the exhaust, but pumped up to a sampling bottle at the surface for later analysis.

Figure 21: Automatic refilling tensiometer

Ridley and Burland (1993) [30] introduced the new concept of measuring suctions greater than 100 kPa and Ridley and Burland (1995) [31] presented a new tensiometer (the so called high capacity tensiometer), which could measure suctions up to 1,500 kPa (see Figure 22). The new tensiometers use a combination of fine porous filters (capable of remaining saturated to 1,500 kPa) and a technique of preconditioning the instrument by pressurising the water in the instrument to very high pressures (e.g. 4,000 kPa).

The hydraulic tension can then be maintained in the tensiometers whilst they remain saturated. If air forms in the reservoir of the tensiometer the tension will reduce instantly to -1 Atmosphere and the water in the tensiometer must be re-pressurised. However, to remove air from the tensiometers using the pressurisation technique, it is necessary to remove them from the ground. Recent developments by Cui et al. (2008) [32] and Mendes et al. (2008) [33] show that tensiometers can be left in situ for long-term measurements under certain circumstances.

Figure 22: High Capacity Tensiometer

Advantages:
- Easy to read.
- Up to 10 cm measurement sphere radius.
- Not affected by salinity, because salts can move freely in and out across the porous ceramic cup.
- Inexpensive.

Drawbacks:
- Limited suction range (in general <100 centibars).
- Relatively slow response time.
- Requires intimate contact with material around the ceramic cup for consistent readings and to avoid frequent discharge (breaking of water column inside).
- Especially in swelling or coarse soils, the ceramic cup can lose contact with surrounding material.
- Requires frequent maintenance (refilling) to keep the tube full of water.

- *Resistance Blocks*

Electrical resistance between electrodes embedded in a porous medium (block) is proportional to its water content, which is related to the water matric potential of the surrounding material. Electrical resistance decreases as the material and the block lose water.

- *Gypsum (Bouyoucos) Block*

A gypsum block sensor is comprised of an electrochemical cell with a saturated solution of calcium sulphate as the electrolyte (see Figure 23). The resistance between the block-embedded electrodes is determined by applying a small AC voltage (to prevent block polarization) using a bridge circuit. Since changes in the material electrical conductivity would affect readings, gypsum is used as a buffer against material salinity changes (up to a certain concentration). An inherent problem is that the block dissolves and degrades with time (especially in saline media), and loses its calibration. The block pore size distribution should match the material texture at the installation site. Readings are temperature-dependent (up to 3% change/°C), so field-measured resistance should be corrected for differences between calibration and field temperatures. Some readers contain manual or self-compensating features for temperature, or the manufacture may provide correction charts or equations. Measurement range is 30 centibars to 15 bars.

Figure 23: Gypsum (Bouyoucos) resistance block and reader

Advantages:

- Up to 10 cm measurement cylinder radius.
- Minimal maintenance needed.
- Simple and inexpensive.
- Salinity effects buffered up to 6 dS/m.

Drawbacks:

- Low resolution, limited use in research: suitable for trend measurement rather than accuracy. Range: -50kPa to –1.5MPa.
- Block cannot be used for measurements around saturation (0 – 30 centibars).
- Block properties change with time due to clay deposition and gypsum dissolution. Degradation speed depends on material type, amount of water and type of gypsum block used. Have limited life, around 5 years in alkaline or neutral environments and 2-3 years in acid ones.
- Very slow reaction time (from few hours to several days). Does not work well in sandy layers, where water drains more quickly than the instrument can equilibrate.
- Not suitable for swelling materials.
- Inaccurate readings due to block hysteresis.
- Temperature dependent. If connecting to a data logging system, another variable and sensor for temperature must be added to the system.

- *Granular Matrix Sensors (GMS)*

The sensor consists of electrodes embedded in a granular quartz material, surrounded by a synthetic membrane and a protective stainless steel mesh (see Figure 24). Inside, gypsum is used to buffer against salinity effects. This kind of porous medium allows measurements in wetter materials and lasts longer than gypsum blocks. However, even with good sensor-soil contact, GM sensors have rewetting problems after they have become very dry because the ability of water films to re-enter the coarse medium from a fine soil is reduced. The GMS material allows moisture measurements close to saturation. Measurement range is 10 – 200 centibars.

Figure 24: Granular matrix sensor (GMS) resistance block and reader

The SIS (see Figure 25) is a combination of the granular matrix moisture sensor and a special amplifier which offers a fully linearised and temperature compensated DC-voltage output signal.

Figure 25: SIS sensor

Advantages:

- Reduces problems inherent with gypsum blocks (e.g. loss of contact with the material due to dissolution and inconsistent pore size distribution).
- Up to 10 cm measurement cylinder radius.
- Minimal maintenance needed.
- Simple and inexpensive.
- Salinity effects buffered up to 6 dS/m.

Drawbacks:

- Low resolution, limited use in research: suitable for trend measurement rather than accuracy. Range: 10kPa to –200kPa.

- Slow reaction time (several days). Does not work well in sandy layers where water drains more quickly than the instrument can equilibrate.
- Not suitable for swelling materials.
- If the soil becomes too dry, the sensor must be removed, re-saturated, and re-installed.

- *Heat Dissipation*

The thermal conductivity of water produces heat dissipation, so a dry material will heat faster than a wet one. In other words, the heat flow in a porous material is proportional to its water content.

A thermal heat probe consists of a porous block containing a heat source and an accurate temperature sensor (see Figure 26). The block temperature is measured before and after the heater is powered for a few seconds. Thereby, block moisture is obtained from the temperature variation. Since the porous block in contact with the measured material is equilibrated with the contained water, its characteristic curve will yield the water potential. Hence, the sensor must be provided with a calibrated relationship between the measured change in temperature and the material water potential. The measurement range is 10 - 3000 centibars (less accurate for 1000 - 3000 centibar range).

Figure 26: Heat dissipation sensor

Advantages:
- Wide measurement range.
- No maintenance required.
- Up to 10 cm measurement cylinder radius.
- Continuous reading possible.
- Not affected by salinity because measurements are based on thermal conductivity.

Drawbacks:
- Needs a sophisticated controller/logger to control heating and measurement operations.
- Slow reaction time (several days). Does not work well in sandy layers where water drains more quickly than the instrument can equilibrate.
- Fairly large power consumption if read frequently.
- Very fragile.
- Devices need corrections for temperature changes and hysteresis.

- *Relative humidity sensors*

Under vapor equilibrium conditions, water potential of a porous material is directly related to the vapor pressure of the air surrounding the porous medium, meaning that material water potential can be determined by measuring the relative humidity (RH) of a chamber inside a porous cup equilibrated with the surrounding solution -Campbell and Gardner (1971) [34].

- *Soil Psychrometer*

In thermocouple psychrometry [35], the temperature depression of the sensing (wet) junction that is measured relative to the reference (dry) junction varies as a function of the relative humidity of air surrounding the sensing junction. A thermocouple is a double junction of two dissimilar metals. When the two junctions are subject to different temperatures, they generate a voltage difference (Seebeck effect). One junction of the thermocouple is suspended in a thin-walled porous ceramic or stainless screen cup in contact with the material, while another is embedded in an insulated plug to measure the ambient temperature at the same location.

Psychrometers are well suited to measure suction in the high range. Limitations of the psychrometer are the necessity of equilibrium through the vapour phase, which causes a relatively slow response time, susceptibility to thermal gradients and difficulties to measure suctions lower than 1000 – 2000 kPa [36]. Large scatter of psychrometer data in the small total suction range (<1000 kPa) was experimentally confirmed by Agus & Schanz, [37].

Thermocouple psychrometers are very sensitive to fluctuations of environmental temperature. Most in situ sensors for field measurements now used have the same basic circuitry and use Peltier cooling to remotely wet the sensing junction. Intensive experimental research on the effect of sensor design on temperature-gradient errors was done [38], [39] and [40].

Soil psychrometer consists of a ceramic shield or screen that forms an air chamber where a thermocouple is located (see Figure 27). The screen type is recommended for high salinity environments. RH in the air chamber is calculated from the "wet bulb" vs "dry bulb" temperature difference. Measurement range is 50 - 3000 centibars (less accurate for 1000 - 3000 centibar range).

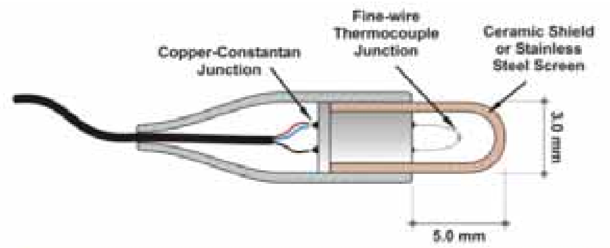

Figure 27: Soil psychrometer

Advantages:

- High sensitivity.
- Scientifically rigorous readings (except in wetter materials).
- Suitable where typical moisture conditions are very dry.

Drawbacks:

- Not recommended when significant thermal gradient is expected.
- Small sensing volume.
- Very slow reaction time, because it takes time to reach vapour equilibrium.
- Low accuracy in the wet range.
- Specialized equipment is required for sensor excitation and reading.

- *Electronic capacitive hygrometer*

The electronic hygrometer is used to calculate the relative humidity of the air. A sample of air is passed through the electronic hygrometer. The electronic hygrometer measures the capacitance. As the humidity of the air increases, the static charge stored in the capacitor rises. This is in the case of the capacitive electronic hygrometer. The resistive hygrometer uses a ceramic material to measure the humidity of the air. As the humidity of the air increases, the ceramic material absorbs the water from the air and this results in a change in the resistance of the ceramic sensor. The amount of current flowing through this ceramic sensor gives the accurate measurement of relative humidity.

Capacitive probes are relatively inexpensive and easy to operate for routine monitoring purposes. They consist of an electrode pair separated by a plastic dielectric (see Figure 28). The resonant frequency of this circuit depends on the capacity of the soil-probe system, which in turn is linked to the soil apparent permittivity. Water content measurements can be performed by relating the resonant frequency to the water content [41].

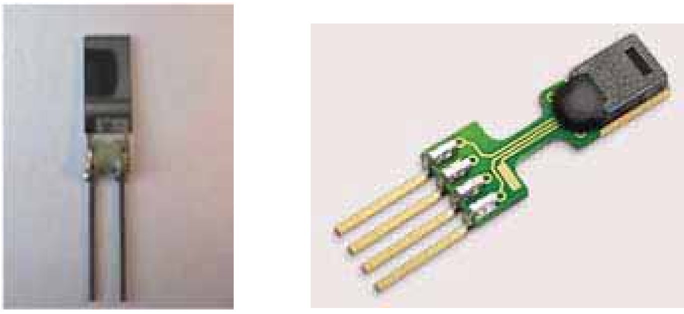

Figure 28: Capacitive probe

Capacitive sensors are characterized by low temperature coefficient, ability to function at high temperatures (up to 200° C), full recovery from condensation and reasonable resistance to chemical vapors. The sensors show a good long-term performance. Although generally specified for a measurement range from 0 to 100 % relative humidity, capacitive sensors lose their accuracy when they become saturated [42].

An important drawback of certain types of capacitive sensors is their cable length. Normally these sensors do not allow cables much longer than 10 m, and besides the cable cannot be cut out and patched as again this produces the permanent failure of the sensor; so, the electronics are fixed at the end of the cable length. This can be a decisive factor to discard this type of sensors in large facilities, where the electronics cannot be emplaced safely out of the repository area.

Advantages:

- Inexpensive and easy to operate.
- Full recovery from condensation.
- Good long-term performance.

- Suitable for high temperatures.
- Small size sensors.

Drawbacks:
- Low accuracy in the wet range.
- Limited cable length.
- Non recovery after saturation

Experiences and results

The election of techniques and sensors for a Nuclear Waste Repository can depend on many different factors and/or constraints. Some considerations extracted from past experiences follow.

Capacitive hygrometers are robust and provide consistent readings. They have proved to be one of the best choices in projects as FEBEX, where they have well surpassed their expected lifetime, withstanding without problems the harsh working conditions, especially regarding mechanical pressure exerted by the bentonite swelling, which was close to 6 MPa. As a drawback, they use to fail once they reach saturation, so in case of subsequent de-saturation of the barrier after reaching 100 % of relative humidity normally they cannot provide readings. In this sense, 60 % out of the 27 emplaced capacitive relative humidity sensors failed after 5 years of operation in the FEBEX experiment [43]. Therefore it is important to avoid preferential flow paths that might conduct free water to the sensor head from the very beginning, before the bentonite has had time to seal the voids, as this would render the sensor unusable. In this sense it can be useful to seal such flow paths, for example in the voids around the cable and the sensor case, with bentonite powder and/or silicone. As an extra advantage, these sensors incorporate directly the electronics, so they provide directly a readable measure.

Psychrometers were also tested in the two large-scale demonstration experiments FEBEX at the Grimsel Test Site [43] and in the VE experiment at Mont Terri [45]. In the FEBEX project, psychrometers turned out to be too weak, as the filter at the sensor head was ceramic over a plastic case. Many of them were crushed at early stages of the experiment by the swollen bentonite. In particular, García-Siñeriz et al. [43] reported that 70% of the psychrometers failed after 5 years of operation. Alonso et al. [42] estimated that half of the sensors failed because of mechanical effects, and the other half as a result of reaching the full saturation status. Therefore, the use of these sensors should be conditioned to the revision of their mechanical characteristics. In addition, due to their reduced range, between 95 % and 100 %, they serve only as an extra support to obtain more resolution data in the final stages of the saturation process, but they are not valid to monitor the entire process, which must rely on other sensor types. On the other hand, both capacitive and psychrometric hygrometers in the VE experiment performed successfully over at least one year [46].

TDR sensors use to be very large in comparison with capacitive hygrometers, and even more compared with psychrometers. This can be an important drawback in zones where the space is constrained, or where disturbance of the barrier with alien elements must be avoided. Readings from TDR sensors can be altered by different degrees of water salinity. This has to be taken into account if differences in this parameter can be expected along time. Besides, both psychrometers and TDRs require an elaborated interpretation of the curves obtained, so they require a careful calibration during installation and specific software to determine the final values.

Using two bentonite-sand mixtures, Agus & Schanz [37] assessed four methods for measuring soil total suction in the laboratory:

- the noncontact filter paper method,

- the psychrometer technique,
- the relative humidity sensor, and
- the chilled-mirror hygrometer technique.

The assessment illustrated the approximate range of the different techniques used for measuring suctions (see Figure 29). The study concluded that the chilled-mirror hygrometer technique appeared to give the most accurate results. The psychrometer method had a slow response and measured smaller total suction compared with the chilled-mirror hygrometer technique. The relative humidity sensor provided the fastest response and appeared more suitable for measuring larger total suction (> 2000 kPa). The chilled-mirror hygrometer, however, is only applicable for laboratory total-suction measurements [44].

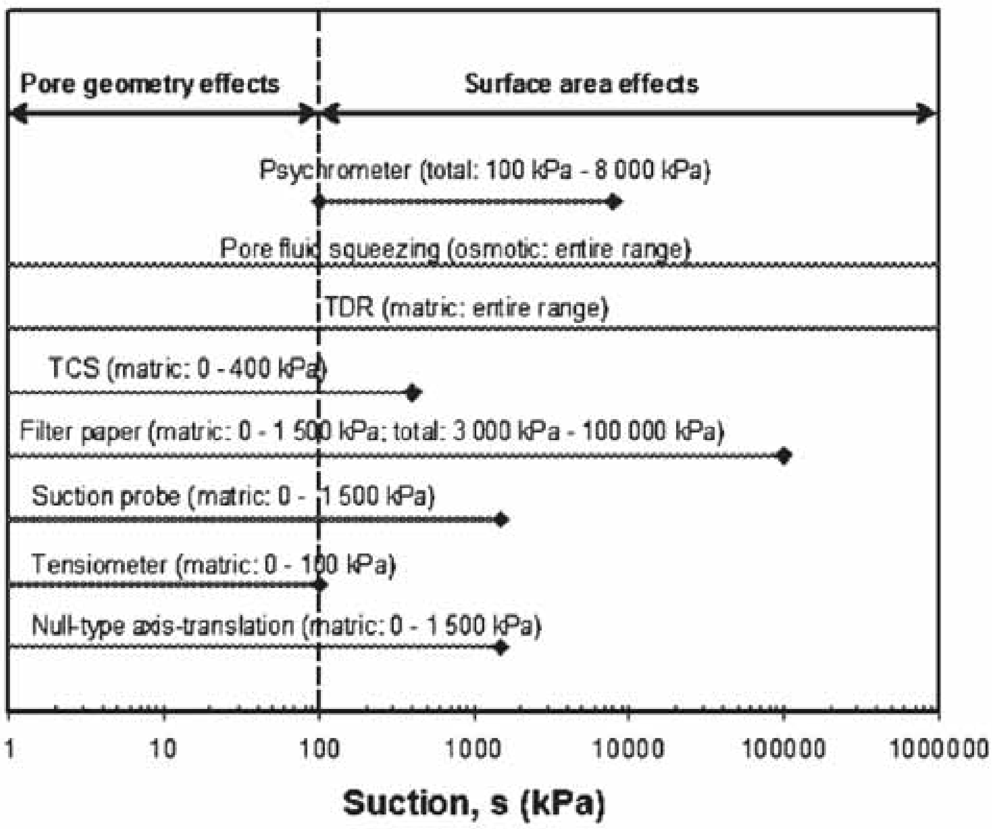

Figure 29: Suction measurement range of several available methods [37].

Context of application within Repository Monitoring
These types of sensors are of application to monitor the degree of saturation of buffer and backfill materials.

References of use in previous experiences
As for temperature and total pressure, water content and humidity sensors are one of the most largely utilised within experiments in underground research laboratories [14], [15], [16], [17], [18], [19], [21], [22], [23] or [25].

Limitations
As already mentioned one of the main limitations of humidity sensors is their sensibility to free water. Many of them, as for instance capacitive and psychrometers, result irreversibly damaged

when they are flooded. Therefore, during their installation it is important to stop any preferential water flowpath that could reach the sensor head.

Another limitation is the poor performance of some of the sensors in different parts of the scale of saturation degree, which makes necessary the duplicity of sensors of different types in one single measuring point to cover the full scale. In particular, it is very difficult to obtain accurate measures in media close to full saturation. Psychrometers are intended for that span, but their readings are difficult to interpret correctly.

Other techniques have particular limitations, as volumetric measures, which are strongly dependent on the media porosity. In clayish media, whose porosity changes with the degree of saturation due to the swelling, a very accurate calibration must be performed in advance to ensure correct measures.

Further developments
The main developments to be addressed refer to the aforementioned limitations, in particular as regards the achievement of accurate measures in media close to full saturation.

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3.1.1.4 Hydraulic pressure

Why measure hydraulic pressures?

Monitoring of hydraulic pressures typically provides essential information on the state and behaviour of the rock or soil under investigation.

In soils, hydraulic pressures are more commonly designated as porewater pressures. Their importance is summarized by e.g. Baligh [47]:

"Porewater pressures occupy a central position in modern soil mechanics for conceptual and practical reasons. Conceptually, effective stresses control most soil behaviour aspects of interest to geotechnical engineers and total stresses are controlled by equilibrium conditions. Hence pore pressures are necessary to estimate effective stresses from calculated total stresses and thus to allow the rational interpretation and/or prediction of the response of soil masses. Practically, the pore pressure in the soil is often easier to measure than other equally meaningful aspects of soil behaviour because it exhibits no directional dependence. This is especially so in field situation involving anisotropic and non-uniform stressing (or straining) of the soil."

Moreover, pore pressure is one of the three essential parameters in the THM-models that are used to describe the soil behaviour and which are used to assess field measurements.

Measurement techniques and implementation

Monitoring of hydraulic pressure in repository of radioactive waste includes at least two cases. The one case is the monitoring of hydraulic pressure in packed off sections in boreholes drilled from drift or shaft in the repository. The other case is the monitoring of pore water pressure in buffers surrounding the waste or backfills in drift or shaft.

The measurement of porewater pressure implies the use of a filter element to separate the water pressure from the total pressure. Typically, sintered steel filters are used, but also ceramic and plastic filter materials are in use. The pore size of these filters (expressed in μ) should be adapted to the environment (e.g. type of clay). A pressure transducer with an integrated filter is also called a "piezometer". Instead of using one integrated transducer, the filter part can be separated from the sensor part by a (twin) tube. This allows to saturate the filter at a later stage (and to remove gas that could build up), to replace/recalibrate the sensor if this is installed at an accessible location, to take water samples and to measure other hydraulic parameters such as permeability.

Particular attention needs to be paid to the application in an unsaturated environment. The initially saturated piezometer can be desaturated by the bentonite (in suction state) around the filter, creating an underpressure. The pressure difference that can be maintained before gas would enter the piezometer through the filter depends on the air entry value. This is typically quite elevated for ceramic filters with small pores. This effect is exploited in the tensiometers to measure suction.

Similar problem could occur for the monitoring of hydraulic pressure in the host rock. For example, in the Mizunami URL, Japan, JAEA (Japan Atomic Energy Agency) is monitoring hydraulic pressure in separated sections of the borehole drilled from a tunnel [48]. The host rock around the borehole is saturated in groundwater by now, and hydraulic pressure sensors are installed at the end of hydraulic lines from different sections of the borehole. Future development of the URL to the deeper area of the host rock and following discharge of groundwater will cause unsaturation around the borehole, and the monitoring at the end of hydraulic lines will become problematic. At that time, the sensors at the end of hydraulic lines are planned to be removed, and smaller sensors will be installed IN the hydraulic lines to monitor the pressure.

A pressure sensor is connected to a data acquisition unit through a sensor cable which supplies electricity to the sensor and records data from the sensor. When a piezometer is installed in a borehole, the sensor cable penetrates seals in the borehole. Similarly, when a piezometer is installed in buffers or backfills, the cable penetrates them. Thus, in the both cases, water-tightness of materials along the cable is important to measure precise hydraulic pressures. The same attention also has to be paid to use hydraulic line for the monitoring. Measurement range has to cover not only the values of hydrostatic pressure at the repository, but should also include the temporary increases due to underground operations (e.g. excavations) or heating (expansion of pore water) or swelling pressure of bentonite. Other technical requirements may include dimension of sensor and long-term stability. If the sensor is installed in buffers surrounding the waste, heat resistance and radiation hardness will be also required.

Several types of electric pressure sensors are available for the monitoring of hydraulic pressure in the repository; piezorresistive, vibrating-wire type, strain-gage type, and linear variable differential transformer (LVDT) type are the most common. Other techniques include pressure sensitive resonant micromachined structures (quartz or silicon made), other types of inductive sensors, and capacitive sensors (with the pressure sensitive diaphragm being one of the two capacitor plates).

Also non-electric sensors are being developed, using of the available fibre optic measurement principles (Bragg grating as a substitute for the strain gauge, or interferometric techniques to measure the displacement of the diaphragm).

Piezoresistive
Piezoresistive transducers rely on the the change of resistivity of a diaphragm under pressure. This diaphragm can be done of different materials, e.g. silica crystal mechanised in blocks by means of chemical attack, or micromechanised titanium.

Vibrating wire
As already commented in previous sections, the operating principle of vibrating-wire (VW) pressure sensor is as follows [49]: the resonant frequency of vibration of a tensioned steel wire is dependent on the strain or tension in the wire. The transducer uses a pressure sensitive diaphragm with a vibrating wire element attached to it. In this case, fluid pressures acting upon the outer face of the diaphragm cause deflections of the diaphragm and changes in tension and frequency of the vibrating wire. The changing frequency is sensed and transmitted to the readout device by an electrical coil acting through the walls of the capsule. As already mentioned, the VW principle offers advantages, such as a robust (frequency based) signal (sometimes also designated as a "digital" signal) that allows long cable lengths, is quite immune against cable degradation, while modern read-out techniques (frequency analysis based) allow also the sensor functioning in noisy environments. As no active electronics are involved in the sensor itself, the principle can be applied also at higher temperatures (up to 200 °C) and at elevated radiation levels. A weak point could be the performance of the tensioned wire at longer term. Especially the clamps at both wire-ends could be important.

Strain gage
In strain-gage pressure sensor, water pressure causes strain in a gage with a resistive element. For strain measurement, a Wheatstone bridge is formed to convert strain-initiated resistance change to a voltage change. Detailed specifications are available in the website of manufacturer [50].

LVDT
Operating principle of linear variable differential transformer (LVDT) pressure sensor is as follows [51]. An LVDT is an electro-mechanical device that produces an electrical output that is

linearly proportional to the displacement of a moveable core. It consists of a primary coil with two secondary coils placed on either side of the primary coil. A rod-shaped soft magnetic core inside the coil assembly provides a path for the magnetic flux linking the coils. A movement of the core leads to an increase in magnetic coupling to the coil in the direction of movement and a reduction in magnetic coupling to the other coil producing a net output signal from the connected secondaries. To form a pressure transducer, the core displacement of the LVDT is produced by the movement of a metallic pressure responsive diaphragm.

Table 2 shows examples of fundamental performance of these different types of sensors.

Table 2: Example of fundamental performance of hydraulic pressure sensors

Type	Measurement range(MPa)	Nonlinearity (%)	Dimension of sensor (mm)	Temperature range (°C)	Reference
Piezoresistive	0 to 140	±0.1 (F.S.)	Φ16 x 40	-55 to 120	http://www.kulite.com/
Vibrating wire	-0.1 to 150	±0.5 (F.S.)	Φ19 x 133	0 to 200	http://www.geokon.com/
Strain gage	0.2 to 2.0	±2 (R.O.)	Φ40 x 100	-30 to 80	http://www.kyowa-ei.co.jp/eng
LVDT	0 to 1.0	±0.5 (F.S.)	Φ35 x 151	-30 to 80	http://www.sakatadenki.co.jp/

For the selection of sensor, type of signal and corresponding devices to measure and store data are also to be considered. Strain gage and LVDT pressure sensors usually output signals in analogue voltage form, whereas vibrating wire pressure sensors output signals in frequency form. A universal measuring device can be used for analogue voltage signals, however frequency signals require a specific device. Laaksonen (2010) [52] noted the possibility to use digital output pressure transducers of e.g., Druck Ltd. England [53].

When the sensor itself is integrated inside the host rock or buffer, and therefore becomes inaccessible, the impossibility of recalibration becomes an important issue. Several techniques have been proposed to overcome this, such as the use of the compensating technique (e.g. as marketed by Glötzl) – involving the use of hydraulic lines. The system tends to be rather complex, both in installation (two hydraulic or pneumatic lines per sensor) and in operation (pumping).

Experiences

Piezometers based on KULITE piezoresistive transducers were developed specifically by AITEMIN for local permeability measurements in the Backfill & Plug Test, in the Äspö Hard Rock Laboratory [54]. They comprised the transducer in the sensor head, inside ceramic filters measuring 50 mm in diameter and 120 mm in length (Figure 30), and also hydraulic lines to perform another measurement outside the test zone, so as to compare both readings. The piezometers were thrust into different layers of a backfill composed of a compacted mixture of crushed rock and bentonite (70-30). Permeability was determined by means of pulse tests. The transducers in the sensor head worked correctly

Figure 30: Dynamic Pore Pressure sensor

Hydraulic pressure has been monitored too in the near field rock of the FEBEX Project. Piezometers were installed in 19 radial boreholes around the gallery, the piezoresistive transducers located in this case outside the test zone. Each borehole was divided in several intervals, between two and five depending on the length, by means of hydraulic packers. Performance of these sensors was good both in terms of results obtained, with coherent measures and good correlation of data, and in terms of reliability, provided that transducers were accessible for replacement upon failure at any time.

Context of application within Repository Monitoring

Monitoring in boreholes from the ground surface will be initiated in a site investigation phase and will be continued at least during closure phase (e.g. Bäckblom et al., 2004 [55]), and hydraulic pressure in the repository-based boreholes will be monitored after construction of repository.

SKB (2010) [56] describes current program of detailed characterization during construction and operational phase. During these phases, monitoring of hydraulic pressure in near field is foreseen to be added in packed-off sections of boreholes from the underground facility. One principal purpose of the monitoring during construction and operational phase is to identify whether and how the facility impacts the parameter in question. The period of undisturbed monitoring data will cover many years before the start of construction of the final repository. Other principal purposes are to provide detailed data for adaptation of the facility to the bedrock and to verify that the design premises are fulfilled. The design processes of underground facilities uses information mainly from borehole investigations and existing models. As construction proceeds, this information is supplemented by the result of investigations and monitoring including hydraulic pressure.

Monitoring of pore water pressure in bentonite buffer and buckfills are another case to monitor hydraulic pressure, however it is not necessarily done in a repository. For example, the Prototype Repository Test (Goudarzi et al., 2010) [57] includes full-scale deposition holes, copper canisters equipped with electrical heaters, bentonite blocks and a deposition tunnel backfilled, and pore water pressure was monitored in bentonite blocks and in backfills using vibrating wire transducer and piezo resistive transducer.

Laaksonen (2010) [58] described instrumentation of similar mock-up test including the monitoring of pore water pressure in bentonite buffer to verify that the conditions surrounding the canister are according to the design requirements. This report also provided list of mock-up tests previously have been carried out.

Similar examples could be found at [16], [17], [18], [20], [21] or [22].

Limitations
One of the limitations is related to the application in unsaturated environments, as discussed in the section of Measurement techniques and implementation. Unsaturated environment will come up in both the monitoring in buffer/buckfill and that in host rock. As is seen in table 1, a large number of commercially-available hydraulic pressure sensors have range of measurable range of pressure higher than zero (MPa). These sensors usually do not work in a negative pressure environment, and sometimes go out of order.

A long term monitoring without accessibility will add another limitation to replace/replace sensors. For hydraulic pressure sensors, clogging of filter to separate water pressure from total pressure may enhance the need for the replacement. Use of hydraulic line eases this limitation, as discussed in the section of Measurement techniques and implementation.

High temperature and corrosive fluid (e.g. saline water) may cause a limitation in the monitoring of repository, especially of EBS. Careful selection of materials of components of sensor and cable connections or application of fiber optic sensors will probably overcome this limitation.

Water tightness along electric cable or hydraulic line may cause an essential limitation in the monitoring of hydraulic pressure. If a conduit was formed along the cable, measured pressure will be not suitable for the purpose of the monitoring. Careful installation of seals along the cable or application of wireless data transmission system will probably overcome this limitation.

Further developments
Wireless data transmission systems with hydraulic sensor are developing in RWMC and Aitemin. The result of development in RWMC will be reported in the MoDeRn International Repository Monitoring Conference and Workshop, and the result of development in Aitemin will be described in the report of Work Package 3 of the MoDeRn project.

Fiber optic sensors with Bragg grading principle have been developed for the measurement of total pressure (e.g. Jobmann, 2009 [59], RWMC, 2012 [60]), and it is being developed for the measurement of hydraulic pressure.

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3.1.1.5 Radiation

Radiation monitoring in waste repositories
Ionizing radiation comprises both high-energy electromagnetic radiation (gamma radiation, frequency >10^{19} Hz) as well as particles (usually high-energy) – of which alpha, beta and neutron particles are the most common.

The total energy deposited in a medium by ionizing radiation per unit mass is the dose, expressed in gray (Gy), which corresponds to 1 J/kg. The dose rate is the energy per time unit (power), expressed e.g. as Gy/h.

Radiation present due to the waste packages can be caused both by the gamma-rays (and optionally neutrons in the case of spent fuel) emitted by the packages, as well as by the radio-nuclides that could spread from disintegrating (leaching) packages.

Measurement techniques
- Detectors

Radiation can be monitored both on-line – as well as off-line. The most common types of the off-line detectors are the thermo-luminescent detectors, which are based on the defects that build up in lattices of selected crystals (e.g. LiF) due to radiation. When restoring the lattice by warming up, the energy is released in the form of a light pulse; measuring this light pulse then indicates the total dose absorbed by this detector. Because this type of monitoring is not suitable for unattended monitoring, it is not further discussed here.

The established on-line detectors for gamma radiation are gas-filled, scintillation and semiconductor detectors [61]. Typical performance indicators for detectors are the efficiency (how many pulses occur for the given number of gamma rays) and (spectral) resolution (capability to separate the different peaks in a spectrum).

A gas-filled detector is basically a metal chamber filled with gas and containing a positively biased anode wire. A (gamma) photon passing through the gas produces free electrons and positive ions. The electrons are attracted to the anode, producing an electric pulse. The voltage applied to the anode determines the mode (Figure 31).

Above a minimum voltage (under which the electrons recombine with the ions before reaching the anode), nearly all electrons are collected – this detector is known as an ionization chamber. It has a very low signal output and therefore makes this detector difficult to use for detecting individual gamma rays. It is used in high radiation fluxes.

At higher voltages the electrons are accelerated at energies high enough to ionize other atoms, thus creating a larger number of electrons - this detector is known as a proportional counter. This type is used where moderate energy (spectral) resolution is required. They are available in different sizes and shapes. Operating voltages depend on the gas used, as well as on the geometry. Detectors can be completely sealed.

When increasing the voltage further, the electron multiplication becomes independent from the initial ionization. This detector is the Geiger-Müller counter. It does not allow energy measurements. Returning to a neutral ionisation state after pulse takes some time (several 100 µs), which limits the counter to low count rate applications. At even higher voltages continuous discharge occurs.

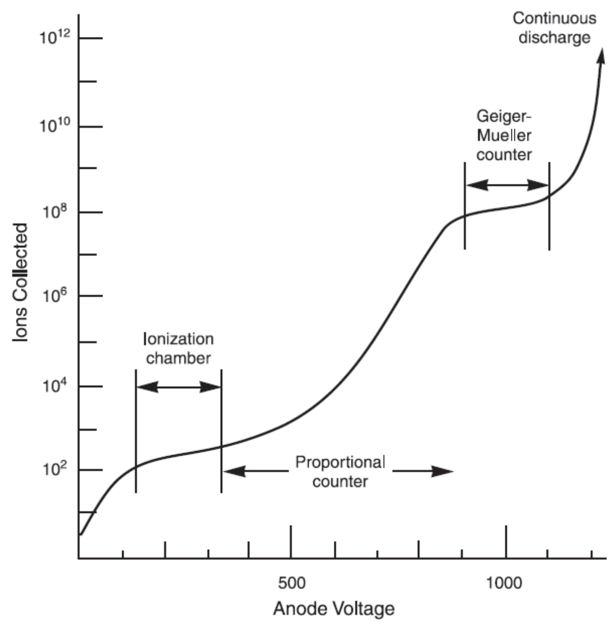

Figure 31: Gas detector output vs. anode voltage

- Scintillation detectors

Scintillation detectors are laboratory-grown crystals that produce a flash of light or scintillation when traversed by radiation. The scintillations are amplified in a photomultiplier tube to which the crystal is optically coupled, and the output is a pulse with amplitude proportional to that of the impinging radiation. This output can be used for spectral logging. The most commonly used scintillation material is thallium activated NaI – therefore designated as NaI(Tl) – as it has a high absorption efficiency for gamma rays, and as it is available in large sizes (typical crystal dimensions are 8 cm diameter by 8 cm long).

Scintillation detectors are e.g. applied in borehole logging [62]. This tool detects variations in the naturally occurring radioactivity originating from changes in concentrations of the trace elements U and Th, as well as changes in concentration of the major rock forming element K.

- Semiconductor detectors

This type of detectors are basically diodes having a p-i-n structure in which the intrinsic (I) region is sensitive to ionizing radiation, particularly x rays and gamma rays. Under reverse bias, an electric field extends across the intrinsic or depleted region. When photons interact with the material within the depleted volume of a detector, charge carriers (holes and electrons) are produced and are swept by the electric field to the P and N electrodes. This charge, which is in proportion to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge sensitive preamplifier. Because of the low band gap of the semiconductors, these detectors must be cooled in order to reduce the thermal generation of charge carriers (thus reverse leakage current) to an acceptable level. Otherwise, leakage current induced noise destroys the energy resolution of the germanium detector. Liquid nitrogen, which has a temperature of 77 °K is the common cooling medium for such detectors.

A range of Ge detectors installed in the HADES underground research facility in Mol (Belgium) is operated by IRMM (Figure 32). This installation is part of a larger network of underground laboratories where gamma-ray spectrometry with high-purity Ge detectors is applied for low-level measurements requiring a very low background level [63]. The installation requires regular maintenance (e.g. weekly refill of liquid nitrogen).

Figure 32: Ge-detectors in HADES

- Conclusion on detectors

All these types of detectors can be considered as "active" sensors, i.e. requiring significant auxiliary components for excitation (high voltages in gas filled tubes), signal conditioning (photomultiplier tubes for the scintillator) or cooling (liquid nitrogen for semiconductor measurements). Their application would be of a quite invasive nature in a radwaste repository context. Long-term, unattended monitoring is therefore unlikely to be achieved with this type of detectors and thus there are no experiences of use for experiments in underground research laboratories. Other types of monitoring equipment should therefore be envisaged.

- Other techniques

A rather new technique to monitor the total dose is based on the radiation-induced attenuation in optical fibres. This technique is discussed in Section 3.1.2 on optical fibre technology.

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3.1.1.6 Displacement

Why measure displacements?

Displacements are liable to occur within the confined space of underground repositories, where high pressures are developed due to the swelling of bentonite. Differences between pressures in nearby zones can give raise for example to displacements of the capsules containing the nuclear waste, or to movements of the different seals as concrete plugs, which in turn can jeopardise their sealing capacity and can produce a variation of the total volume confined and hence the total density of the barrier. Tilting can occur too in elements within the barrier and in sealing elements.

The displacement measure is carried out normally between two points, and use to be a relative measurement rather than an absolute position measure, that is, the magnitude measured is the displacement occurred from the initial position between those two points, one of them normally being a reference point in the rock, and the other a point in the element whose displacement is to be monitored. Tilting is measured by means of tiltmeters attached to the elements to be monitored.

Techniques and signal characteristics.

Some well proven techniques are available to measure displacement:

- Displacement potentiometric transducers

These transducers are based on a very simple, low cost design and provide a high level direct signal which requires no additional conversion. For these reasons these sensors are widely used in a variety of applications.

They are based on the displacement of a sliding contact, which is mechanically attached by means of a rod to the moving part to be monitored, over a resistive element, producing a circuit with variable resistance.

Two main layouts are used: linear and circular potentiometers. The resistive element consists of a wire coiled up around an isolating support. The wire can have a diameter of 0.01 mm, so as to obtain a good resolution. Lower diameters can increase the risk of wire break. There is another type of potentiometer where the resistive element is a film, which provides a much higher resolution, in the order of 0.01 μm, limited by the grain size of the material used to settle the film.

Typical values of the total resistance of the potentiometer are between 1 kohm and 100 kohm, reaching in some cases several Mohm, although this is not recommendable as it increases the sensitivity to electromagnetic interference.

- Displacement inductive transducers

These transducers are based on transferring the displacement to be monitored to an element in a magnetic circuit, which provides a variation of flux through a coil used to obtain the signal.

Basically they can be sorted in two groups: movable core and movable coil transducers. In the first group, the displacement can be detected by the variation of self-induction in a coil, or by the coupling ratio between primary and secondary coils. In the second group, the movable coil acts as an inducer circuit, which along with a fixed coil acting as an induced circuit compose a variable coupling ratio transformer depending on the displacement of the movable coil.

The most extended type is linear variable differential transformer (LVDT). A more extense description of its operating principle was included in Section 3.1.1.4: two secondary coils are placed aligned at both sides of an excited primary coil, and a moving core is placed inside, its movement producing a variation in the magnetic coupling between the primary coil and both secondary coils. In this case, the movement of the core is caused by the movement of the element to be monitored, to which it is joined.

- Displacement capacitive transducers

These transducers are based in the same principle mentioned in Section 3.1.1.2. Capacity of a condenser varies by changing either the distance between plates, the effective area of the plates or the dielectric constant of the media between them. In this case, the displacement of the element to be monitored causes 1) the perpendicular displacement of one of the plates towards or apart from the other, 2) the parallel displacement of one of the plates to overlap more or less with the other, or 3) the greater or lesser insertion of a dielectric material between both plates.

- Displacement vibrating wire transducers

These transducers rely on the same principle described in Sections 3.1.1.4. and 3.1.1.7. In this case, the displacement of the element to be monitored causes a change in the tension state of the vibrating wire within the transducer, thus changing the reading obtained.

Besides of the above, some other transducers are available, such as encoders and a variety of non-contact transducers: optoelectric transducers, variable reluctance transducers, eddy current transducers, Hall effect transducers, magneto-resistive transducers and proximity capacitive transducers. These non-contact displacement sensors have very limited application in a repository, given the harsh working conditions that can affect the measurements and the small ranges in comparison with the scale of a repository, so normally the measurement of displacement in a repository requires direct contact between the two points that are being monitored.

- Tiltmeters

The most extended type is the bubble one. It consists of a small tube containing an electrolytic solution with a small bubble in it. Two electrodes at both sides of the tube are connected to the data acquisition system. The amount of current passing through the electrodes will be affected by the portion of electrode in contact with the bubble, which is directly dependent on the inclination of the tube. Biaxial tiltmeters feature two of these tubes in a perpendicular array.

Accuracy.

LVDTs provide an excellent response in terms of resolution, only limited by the signal acquisition system, and of linearity in the linear section of the full range, approximately the central third of the full range.

Tiltmeters are quite accurate, obtaining precisions in the order of 0.1 μradian.

Long term performance and reliability.

Displacement potentiometric transducers have low variation with temperature and are quite robust in general. Their lifetime is dependant on the wear of both the sliding contact and the resistive element due to friction, which in turn depends on the speed of the displacement and the total distance covered by the sliding contact. This is normally the main drawback of these transducers, but the displacements expected in a repository are very slow and normally in one direction only, so practically no wear can be expected in that contact. Potentiometers were used in the Tunnel Sealing Experience [64] to measure displacement of a clay bulkhead.

LVDTs feature no mechanical couplings between coils and core, which grants repeatability and long lifetime, showing a very low hysteresis, below 0.002 % of f.s. They have been widely used to measure displacement in different experiments, as the Tunnel Sealing Experiment [64], where they showed a good performance in general. In other cases, those embedded into a buffer have resulted less reliable than vibrating wire sensors, as in the FEBEX case, where they failed fairly soon in comparison. In FEBEX [21] and other projects as ESDRED [20], these sensors have been installed to measure potential displacements of a concrete seal, with good results as they were not embedded in a buffer, but installed in the service area.

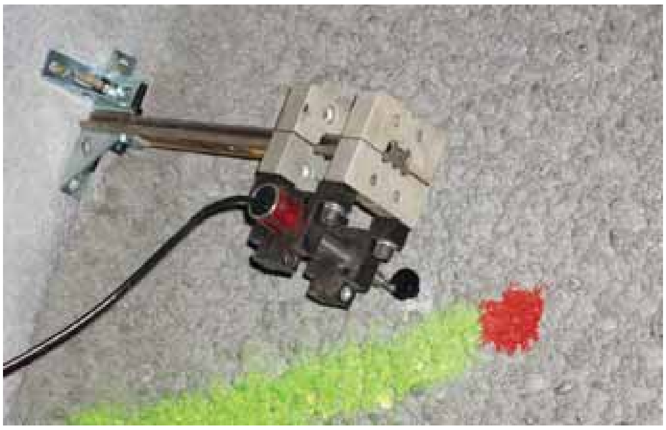

Figure 33: LVDT for measuring concrete seal displacement in ESDRED experiment

Vibrating wire transducers are quite robust, and have shown a good performance in projects as FEBEX [21], where they were used both to measure the heater displacement and the change of size of bentonite blocks. Although some of the sensors installed in this experiment failed well before their expected lifetime, this was due to the severe corrosion they bore, which was favoured by the environmental conditions in the bentonite [43]. This was independent from their measuring principle, and they worked correctly during the time they were functioning.

Installation

Contact displacement transducers require in general two supporting points, so that they measure the relative distance between them. These can be both moving points, as for instance the transducers measuring the width of a given bentonite block, or sensors embedded into concrete, or one of them can be fixed, so that an absolute distance can be measured, such as the vertical or horizontal distance of a canister to the rock.

In the first case, the sensor is "floating", for example within the bentonite barrier. A usual requirement is that the device containing the transducer be spring-loaded, so to keep track of the element when an elongation occurs. It is important that the strength of the spring is not excessive, to avoid altering the measure.

Figure 34: Bentonite block displacement sensor in FEBEX

In the second case, an anchoring to a reference point is required, which usually is the surrounding rock, and another anchoring point is required to the element to be tracked. If this distance is long i.e. one or two meters, and the sensor will be embedded into a bentonite buffer that will eventually swell, it is important that the elements covering the distance between the two points are sufficiently robust so to withstand the expected swelling forces without bending, as was the case with some of the canister displacement sensors embedded in the bentonite buffer of FEBEX [21]. These sensors can be seen in Figure 35.

Figure 35: Canister displacement sensors in FEBEX

Aside of the usual measures for preventing corrosion that must be taken into account when installing sensors in a repository, special care must be taken to avoid galvanic corrosion in the anchoring points, especially if the presence of salty water is expected. Thus, if the element to be tracked is metallic, the anchoring part of the sensor in contact with that element must be made of the same metal, or of a metal of similar potential. Otherwise, a non-metallic material must be inserted in between to avoid this contact.

Particularities
Capacitive transducers provide a high impedance signal with a high excitation voltage. As for other sensors using this measuring principle, vibrating wire transducers for displacement measurement require temperature compensation, as well as dedicated data acquisition units to convert the signal to digits, and still another conversion is required to convert them to displacement units. The other transducers considered provide analog signals that can be read by standard acquisition units.

Conclusions
In harsh environments where a robust displacement sensor is required, as in the case of a repository, vibrating wire transducers are the most reliable choice and hence the preferred one, despite their drawbacks, as need for temperature compensation and need for dedicated signal conversion. Apart from their robustness and immunity of the probe in harsh working conditions even with salty water, they present other advantages as signal transmission over long distances, and immunity to cabling effects. Other options can be considered too, as LVDTs or potentiometers, but they can be more sensible to the environmental working conditions and they are not so robust.

Context of application within Repository Monitoring
Different components of the repository can require tracking of movement, as the capsules containing the nuclear waste, and the different seals as concrete plugs. In particular, undesired displacements of such plugs can jeopardise their sealing capacity and can produce a variation of the total volume confined and hence the total density of the barrier.

References of use in previous experiences
As a reference of displacement sensors for monitoring the seal plug of a repository, the Integrated Project ESDRED comprised the monitoring of displacement of low pH shotcrete plugs for repositories. Two plugs were constructed in horizontal galleries, one of them in the Äspö URL, and the other in the Grimsel URL.

In the Äspö URL, a 1 m long, 1.8 m diameter cylindrical low-pH shotcrete plug was constructed in a dead-end gallery, leaving a chamber behind. Water at high pressure was injected in that chamber to achieve the plug failure. Three LVDT sensors were placed anchored to the rock to monitor the moment where the failure occurred, and the displacement rate during the moments afterwards. The sensors were placed in the periphery of the free face of the plug, in a 120º array.

In the Grimsel URL, a 4 m long, 3.5 m in diameter low pH shotcrete plug was constructed in a dead end gallery, leaving 1.5 m of bentonite buffer behind. Four LVDT sensors were placed, three of them in the same array as foor the Äspö plug, and the fourth placed in the center of the plug.

As a reference of displacement sensors placed within the bentonite barrier, the previously described FEBEX project can be mentioned.

Limitations
The range of displacements expectable within a repository is not large, so normally are within the sensors scale. However, in most of the occasions it is necessary that the sensors be physically in contact with both parts whose relative displacement is to be tracked. This can be an important drawback in an actual repository, where operators have to make these attachments in presence of radiation.

In this sense, one limitation of these sensors is the inapplicability of non contact sensors within the barrier, given the harsh conditions of humidity, temperature and pressure to be withstood. This type of sensors uses to require a void space between the sensor head and the surface to be tracked, and are quite sensitive to the presence of water, in particular if it is salty. Besides, they have a limited range and require a close proximity to the object to be tracked.

Besides, as already mentioned many of these sensors comprise electronics in the sensor head that can be affected by those expected harsh conditions, shortening their expected lifetime.

Finally, their large size in some cases is another drawback in zones constrained.

Further developments
One of the main developments that can be addressed to increase the applicability of displacement measures in the vicinity of the radioactive waste is the improvement of non-contact sensors, in terms of range and sensitivity to harsh environments as the use of these sensors would reduce the requirements of operators for their installation.

References

[64] Chandler N.A. et al. (2002). The five year report on the tunnel sealing experiment : an international project of AECL. Rapport JNC, ANDRA and WIPP, n° AECL-12127

3.1.1.7 Deformation

Why measure deformations?

Knowledge of mechanical stresses to which a structure is subjected under predetermined conditions of use is a key element in assessing the safety of its operation. Mechanical stresses lead to deformation of the medium. In principle, the theory of Strength of Materials links stress and deformation. Hence, measurement of deformation at specific positions can reveal the stress sources.

Techniques and signal characteristics

Measurement of deformation is generally done between two points (convergence). So, sensors measuring the deformation are generally attached to these points.

Sensors of deformation are also known as extensometer and strain gauge. Technology exists for both deformation measurements conducted at the surface of a support, or within a material (e.g. a liner).

The most commonly used sensors of deformation are resistive gauges: they are small and thin and aim at measuring the deformation very locally. They are easy to install: they are glued or stuck on a surface (see Figure 36).

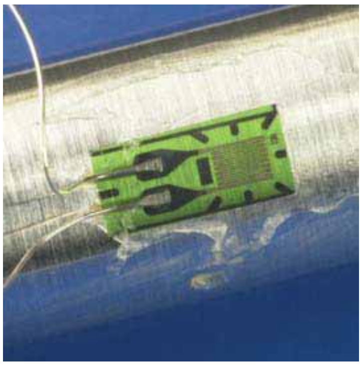

Figure 36: Vishay gauge

The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.

Resistive gauges are available for various applications. Typical measurement range is about +/-5%. Its sensitivity is strongly dependent on temperature variation in a nonlinear way.

Optical fibre can also perform deformation measurement punctually or distributed along the fibre. This will be detailed in chapter 3.1.2.

The easy and simple method of measuring the rock responses is convergence measurement, where the relative distance between several sets of pins on the boundary of an excavation is measured, typically manually with a special tape (Figure 37), or with an Invar wire stretched between studs permanently placed on the surface (Figure 38). This setup permits to remove the instrument and let the framework free between measurements. Invar wires allow achieving typical measurement resolutions of 0.1 mm for deformations over a fairly large base (such as a gallery diameter). The convergence tape measures changes in length between two fixed points over distances of up to 30 meters. The accurate digital gauge provides a resolution of 0.01 mm with a repeatability of 0.05 mm, but the practical measuring accuracy can be considered to be $2 \cdot 10^{-5} \cdot$ measured distance, e.g. the accuracy for a 5 m tunnel span is 0.1 mm. The convergence system always consists of a calibration frame. For monitoring the convergence measurements are then repeated at regular intervals.

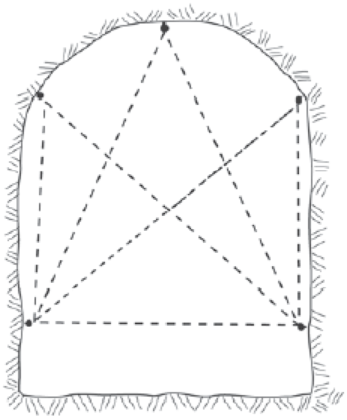

Figure 37: Principle for convergence measurement in a tunnel.

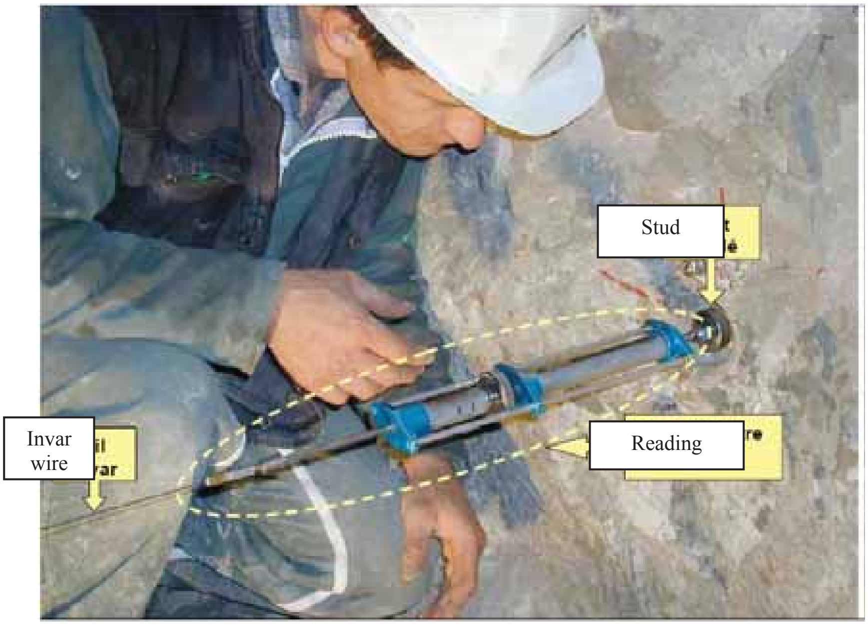

Figure 38: Measurement in the main shaft in Meuse/Haute Marne laboratory (2002)

Invar wires and convergence tapes are very commonly used for displacements monitoring, but more recently geodetic or laser based measurements are gaining increased acceptance in tunnel deformation measurements. This is particularly relevant for tunnelling, where accuracies of +/- 1 mm are often considered to be sufficient. However, in the crystalline hard rock where measured displacements are quite small, geodetic measurements are not applicable.

These geodetic measurements are done with theodolites. A theodolite is a precision instrument for measuring horizontal and vertical angles. Placed among various targets, it allows to calculate the displacement of targets relatively to the others (some considered motionless). Theodolites allow achieving typical measurement resolutions of 0.1 mm for deformations over a fairly large base. Associated measurement uncertainties are mainly linked to the stability of the targets.

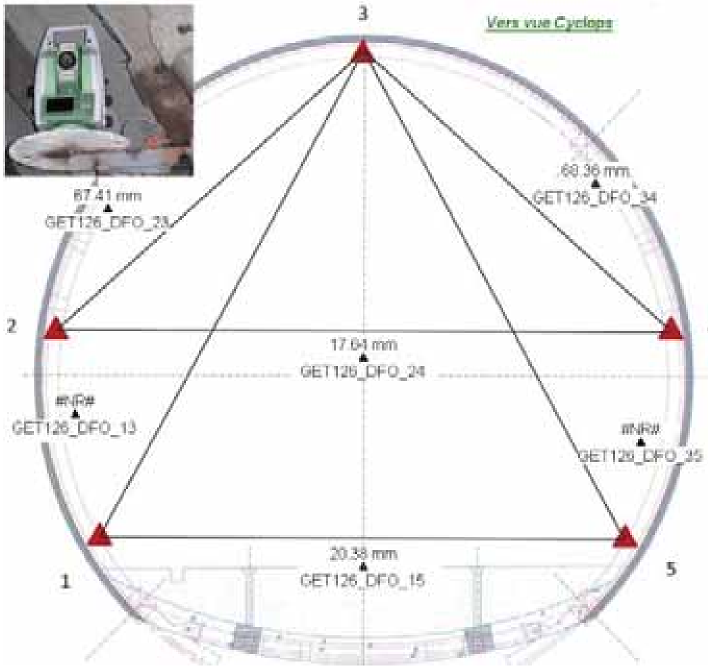

Figure 39: Measurement in gallery GET (2010)

In many projects convergence measurements have worked well, but e.g. in the shaft convergence measurements in the ONKALO at six locations at levels -180 and -290 m between 2007 and 2010 the measurements partly failed. Convergence measurements by Distometer were primarily designed to measure immediate shaft excavation (raise boring) responses and secondarily to be used for monitoring purposes, but in the majority of the measurement campaigns, it was not possible to achieve the preset measurement repeatability of 0.3 mm. During the latest measurement campaign, it was discovered that the measurement device can produce an unexplained variance of almost one mm [65].

There is also an automated convergence measurement method called Bassett convergence system (Figure 40). It is suitable for locations where manual measurements are impossible to conduct like e.g. existing subway tunnels. The Bassett system uses uniaxial tilt sensors to monitor the position of reference pins installed in a tunnel section. The sensors are linked to the pins via a system of low-profile arms. Spatial displacement of the pins results in changed tilt readings. A complete survey of a typical tunnel section requires a few seconds. Seconds later, a computer automatically retrieves the tilt readings from the datalogger in the tunnel, calculates displacement data, and generates a graphic display. The system uses shielded cable with four 22-gauge tinned-copper conductors and polyurethane jacket attached to the transducer at the factory. The Bassett system can detect deformations as small as 0.02 mm, but the practical measuring accuracy can be considered to be around 0.5 mm.

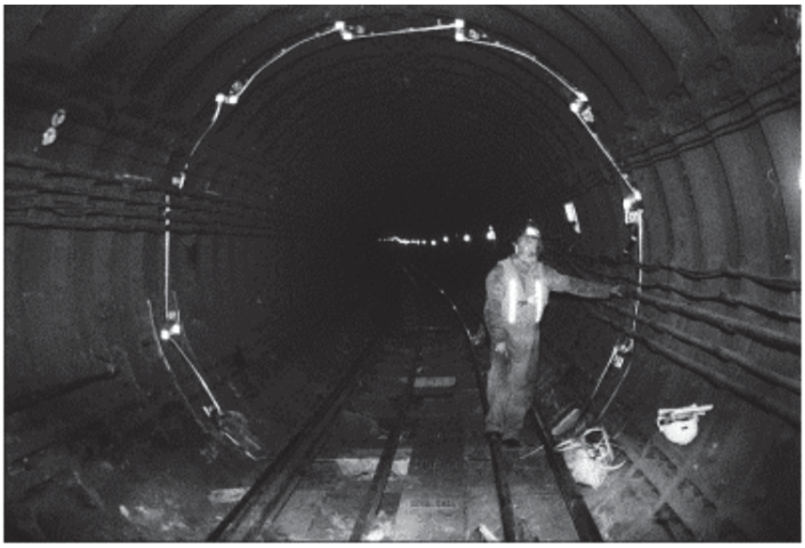

Figure 40: Bassett convergence system in a tunnel.

As a special application the convergence measurements can be used to measure displacements of a fracture zone. This has been done several years in the Olkiluoto VLJ-repository (final repository for operating waste). The relative changes in length are measured on a fracture zone that cuts the access tunnel in four locations over a vertical depth interval of 10 – 70 m (Figure 41).

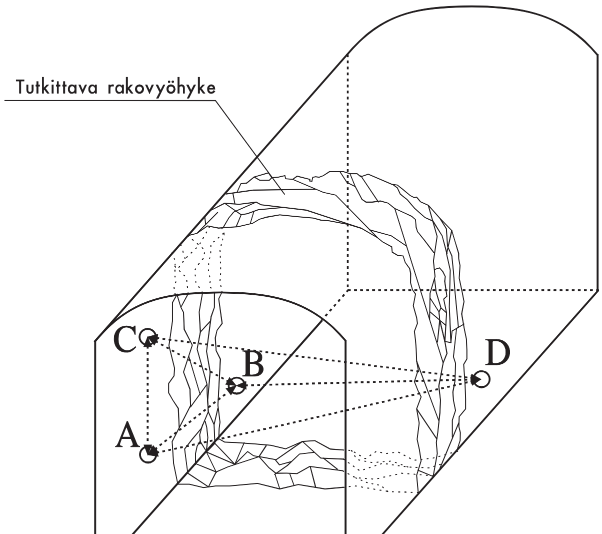

Figure 41: The principle of monitoring movements in 3D in a fracture zone at the Olkiluoto VLJ-repository. The distances between convergence pins A-D are measured.

There are also instruments called jointmeters or crackmeters that are used to monitor movements at single rock joints (Figure 42). Signal cables are similar to those used for Bassett system.

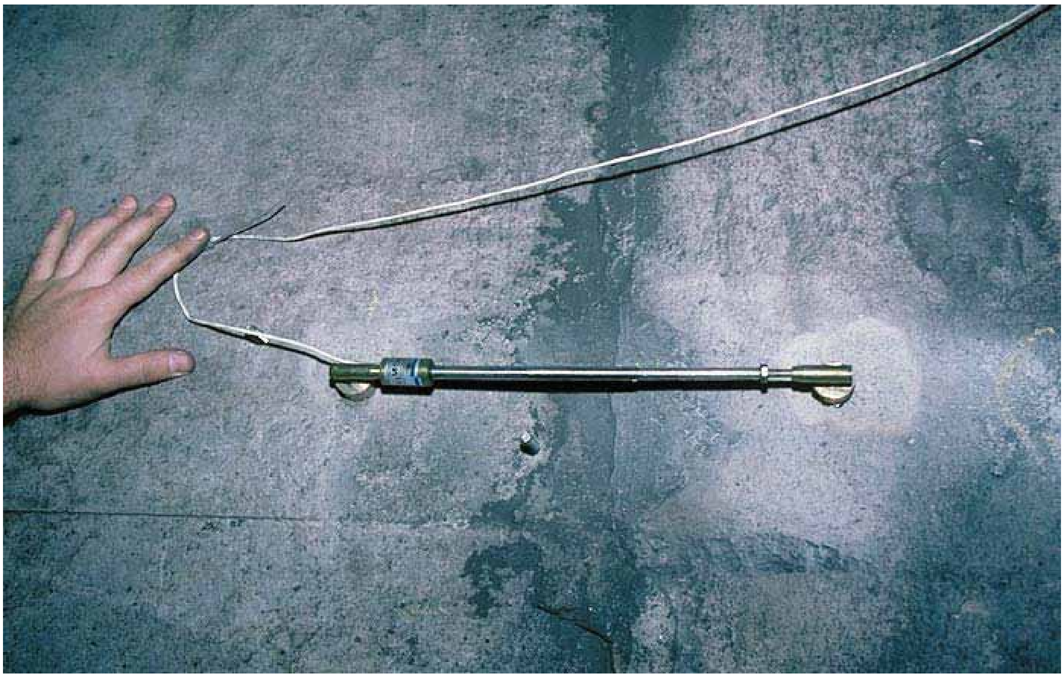

Figure 42: Jointmeter on tunnel wall to monitor rock joint opening/closure.

In Civil Engineering, the deformation measurement has to be done not only at the surface but also inside the medium. In the case of concrete work, the use of vibrating wired extensometer is very adequate: this kind of sensor has been used for many decades in Civil Engineering, it is very robust and can be placed inside and outside the medium.

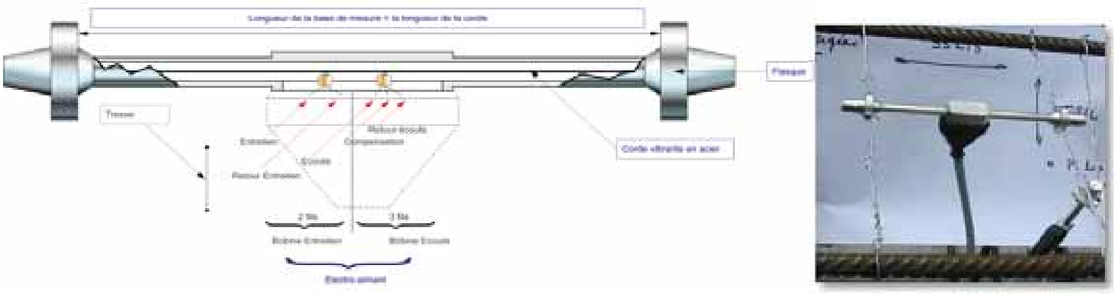

Figure 43: Sketch of sensor type C110 (left) and picture of the sensor before concreting (right)

Andra's monitoring system foreseen for underground repository uses this type of high-performance sensor.

Historically, a patent has been filled in 1931 by André Coyne. So, the first experiments started in 1932-1934. Some vibrating wire sensors (VWS) installed in dams (Le Mont Larron, etc.) are still working since 1950 up to now.

VWS are made of robust materials known for their longevity. The principle of the measurement is based on the vibration of a steel wire. The simplicity of the measurement provides a fail proof system that does not require any drift correction and periodic maintenance. Measurement ranges and resolution are expressed in microdef ($\varepsilon = 1\mu m/m$). Typical full range is about 3000 ε and the precision is +/- 0.1% of the full range. Associated measurement uncertainties are mainly dependent on the concrete behavior regarding the effect of temperature and water content. These types of sensors can be used for temperature ranges of (from –20°C to 80°C). They are not sensitive to humidity. They are robust to mechanical pressure and abrasion, consistent with installation in situ and pouring of concrete over the steel reinforcements to which these sensors are typically attached.

Feedback has now been gathered for more than 60 years. The general principle as described by Andra (2004) is that a vibrating wire sensor (VWS) is made up of a fine steel wire stretched taut between two points, and generating a signal whose frequencies lie in the audible range (500 to 1,200 Hz). In a general way, the wire is made to vibrate, and if the tension varies, this leads to a variation in frequency. It is worth noting that there are four main types of VWS: single electromagnet, double electromagnet, permanent magnet, or nonmagnetic wire with a permanent magnet. For observation and monitoring of the disposal facility, Andra has concentrated on twin-coil VWSs for their greater potential durability linked to an operating voltage that is ten times lower than for the others.

There are also several types of operating mode: damped, maintained and frequency sweep. In the case of maintained operation, which is currently preferred for monitoring of the future disposal facilities, the sensor has two electromagnets and its steel wire is set into vibration and "maintained" in that state by a pair of electromagnets.

This monitoring method has currently been adopted for two reasons: i) The power supply voltages are ten times lower than those used in damped mode, and ii) the wire vibration amplitude is smaller, thus considerably reducing the electronic and mechanical stresses on the sensor in the same proportions. Moreover, sensor readings can be obtained in damped mode in the event of a coil failure.

On starting measurement, the operational amplifier in the measurement station is used to power the first electromagnet with alternating current at constant amplitude and a voltage of 160 mV, called the "Maintaining" signal, which sets the wire vibrating. By induction in the second electromagnet, the wire's oscillations then generate a return alternating current whose voltage ranges between 8 and 24 mV, called the "Listening" signal. The frequency of this low-intensity alternating current is measured. The frequency meter dedicated to the "Maintained" measurement measures and displays the wire vibration frequency, and gives off the corresponding sound via a loudspeaker.

VWSs are still undergoing development, in particular for operators of nuclear power stations, to enhance use of the measurements obtained and also to harden the units in the light of the environment of use and the levels of radiation. The various studies launched are mainly aimed at enhancing use and processing of measurements, especially concerning VWSs, but the studies also cover other measuring principles (TDR, fibre optics, etc.). The procedure is thus aimed at de-correlation of thermal, hydric, mechanical, chemical and radiological influences. It is also worth noting that Andra has obtained internal feedback, especially from the CSFMA disposal facility, where VWSs were installed in the 1990s, and more recently in the Andra Underground Laboratory, in particular in the access shafts.

Although VWSs are based on a simple principle, they are not easy to use. Nonetheless, many uncertainties were dispelled in the spring of 2008, when the fifteen years of measurements made by the vibrating wire extensometers embedded in 1994 in CSFMA facility E5R2 were processed using the "ConcreteLife" method developed by Andra and the Cementys Company. The originality of the method lies in execution of a control test sample that enables elimination of the thermal effects from the overall measurements provided by vibrating wire extensometers, together with the influence of concrete shrinkage and creep. Such cracking as may occur in the facilities can thus be distinguished from the variations linked to daily, seasonal or ageing effects. The structural deformation is analysed from the initial setting and hardening of concrete after pouring, through long-term ageing of concrete in its environment (carbonation, lixiviation). Using the fact that these thermal, chemical (hydration of recently poured concrete), hydric (drying) and mechanical phenomena occur along different time scales, the *Concretelife* method *(*Figure 44*)* provides a retroactive approach that enables progressive de-correlation of the chain of deformations measured.

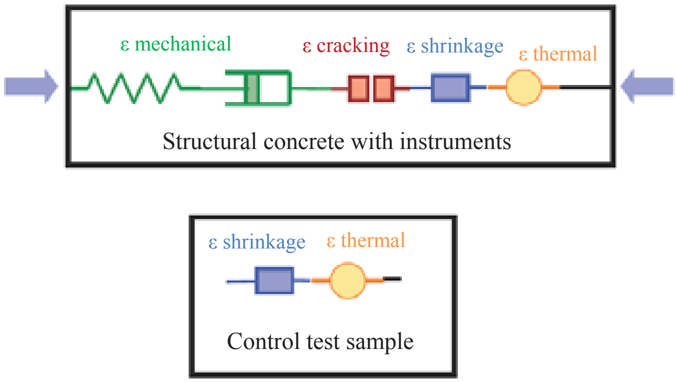

Figure 44: Principle of de-correlation for the chain of deformations using the Concretelife method

To access the purely mechanical deformations, it is necessary to estimate the deformations due to shrinkage and thermal expansion as such. The shrinkage and thermal deformations can be estimated on the basis of control test samples with the same composition and subjected to conditions that are representative of those found *in situ*.

Repository-based monitoring of rock deformation comprises also monitoring of deformation in the near field. The most common monitoring tool is an extensometer placed in boreholes surrounding the galleries. The extensometer measures displacement along the borehole axis. Components of a typical rod extensometer include anchors, rods with protective tubing, and a reference head (Figure 45). The anchors, with rods attached, are installed downhole. The rods span the distance between the anchors and the reference head, which is installed at the borehole collar. Measurements are obtained at the reference head with a sensor or a depth micrometer, either of which measures the distance between the top (near) end of the rod and a reference surface.

A change in the distance, found by comparing the current measurement to the initial measurement, indicates that movement has occurred. Movement may be referenced to a downhole anchor that is installed in stable ground or to the reference head, which can be surveyed. The resulting displacement data can be used to determine the zone, rate, and acceleration of movements, or to calculate strain.

The rod extensometer can monitor up to several points along the borehole. The number of monitored points is limited by the size of the borehole, the type of anchor used, the diameter of the rods, and the amount of tubing required for grouting and activating anchors. A two-point extensometer typically requires a 60 mm borehole; a four-point extensometer requires a 76 mm borehole; and a six-point extensometer requires a 96 mm borehole. Borehole size for packer anchors depends on number of anchors. Signal cables are similar as above mentioned for Bassett system. The practical measuring accuracy can be considered to be ±0.05 mm.

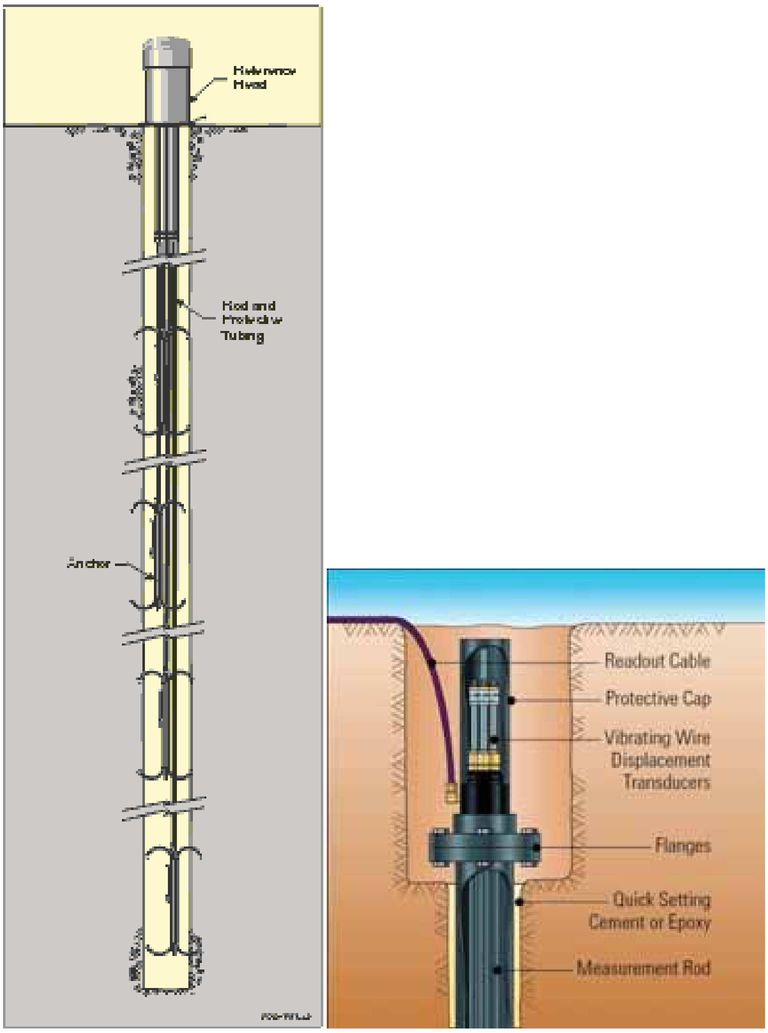

Figure 45: Rod extensometer (left) and reading head (right).

Recently extensometers based on fibre optic deformation sensors have been tested. They are able to measure deformations between two points in a structure, which can be from 20 cm up to 10 meters (or more) apart with a resolution of two microns (2/1000 mm) even over years of measurements. The system is composed of optical deformation sensors adapted to borehole or surface mounting, the cable network, the reading unit and the data acquisition and analysis software. The system is particularly adapted to precise short and long-term monitoring of deformations. First experiences in hard rock environment in Finland have not been very promising and more testing is required.

There are also inclinometers that are used to monitor lateral movements in embankments and landslide areas, deflections of retaining walls and piles, and deformations of excavation walls, tunnels, and shafts. Since inclinometer are based on measuring angles the practical measuring accuracy can be considered to be only around 0.2-0.5 mm. Inclinometers are not much used in hard, crystalline rock conditions.

Case example:
The Olkiluoto VLJ repository has been monitored systematically since its construction in the late 1980s and the rock mechanics monitoring programme also consists of rock displacement monitoring (tape convergence measurements and 18 extensometers) (Figure 46). Extensometer boreholes are fully grouted. Extensometers are read daily by a datalogger (type CR10) and convergence measurements are performed currently only once in five years. In Olkiluoto all signal cables to datalogger are well protected i.e. placed in cable duct covered with the shotcrete layer. The sensors are vibrating wire transducers which are designed for long term monitoring. Advantages of vibrating wire transducers are that they can transmit signals over long cables, are not influenced by water or moisture, are easily data logged and are robust. The performance of the extensometers in the VLJ repository has been good. Some observed negative aspects are that some reading heads of extensometers had to be replaced due to the condensed water. Also, readings are occasionally influenced by electrical interference (spikes).

Similarly Loviisa VLJ-repository has been monitored since 1997 and the rock mechanics monitoring programme has also consisted of rock displacement monitoring (tape convergence measurements, 14 extensometers and jointmeter). Extensometers and jointmeter are read daily by a datalogger and convergence measurements are performed semiannually. In Loviisa repository fibre optics cables have been used. The performance of the instruments has been good except for one break due to lightning that stopped the system. A description of the monitoring programme, results and experiences for both VLJ repositories with a more detailed discussion can be found in Öhberg et al. [66]. Table 3 summarises the techniques described.

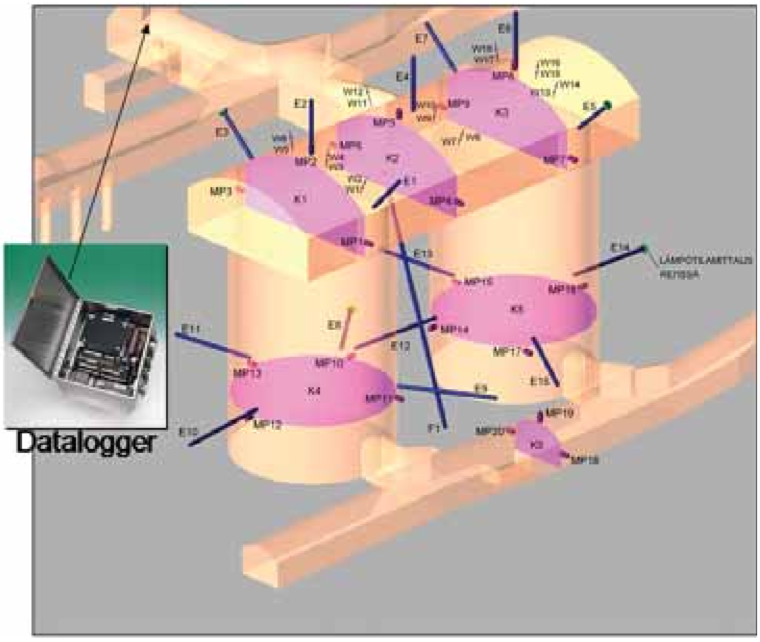

Figure 46: Rock displacement monitoring around the waste silos in the Olkiluoto VLJ-repository. Blue lines are extensometers and mauve cross-sections for the convergence measurements [66].

Table 3: Summary table:

Technique/ Method	Parameter	Application	Monitoring area	Measuring accuracy	Confidence
Convergence	Displacement	Displacement changes	Rock around Repository/Fracture zone	0.1 – 0.5 mm	medium
Extensometer	Displacement	Displacement changes	Rock around repository	0.05 mm	high
Jointmeter	Displacement	Displacement changes	Rock fracture	0.05 mm	high

Context of application within Repository Monitoring:
Deformation monitoring during the construction and operation phase is recommended. Detailed monitoring plan depends much on the repository layout, rock type (how stiff is the rock), groundwater (environment) conditions or existence of critical locations based on the geological information or stability analyses. Since the operation time is long much attention must be paid to long term stability of the instrumentation. Plan should be made that it includes the ability to measure rock responses during the construction phase and ability to continue the measurements during the operation phase. It is important to be able to confirm and check the predicted rock mass behaviour against the observed responses.

References of use in previous experiences
- Two operating waste repositories in Finland [66].
- Operating waste repository (SFR) in Sweden, which has extensometer based deformation monitoring system around the waste silo and in a fracture zone.
- Interim storage facility for all spent fuel CLAB in Sweden, which has also extensometer based deformation monitoring system around the waste storage [67].
- Demonstration experiments in underground repositories as FEBEX [15] or Prototype Repository [18]

Limitations
There are not actually any major limitations but there are several aspects that should be considered. Some instruments are not so suitable for long time monitoring. Some environmental conditions may cause some concern; e.g. extensometers have been replaced several times due to the corrosive environment at SFR in Sweden. Also in the VLJ repository some extensometer reading heads had to be replaced due to moisture (sealing problem). Temperatures need to be monitored always at the same time as the displacements for temperature correction.

Protection of the instrumentation (plus cables) must be planned and implemented with care. For instance, traffic and blasting (if D&B method is used) can damage the instrumentation.

Another issue is that based on current experiences both in Finland and Sweden it has been found easy to add additional data points, but even after consultation with the authorities it has been difficult to remove monitoring locations that seem to be of less interest. The monitoring programme thus clearly should state the duration of measurement campaign and conditions for removal of monitoring locations.

Further developments
Some instruments, although designed for underground monitoring, are not fully prepared to work in those conditions; e.g. water tightness and long term behaviour are still problematic. Instruments are still mostly designed for normal civil engineering projects and not really for nuclear waste repositories.

Theodolite type of 3D-methods are fascinating since they are fast and could be nicely automated but they still suffer from limited accuracy, especially in hard, stiff rock conditions.

Fibre optics is also a tempting methodology, but experiences (in Finland) so far have not been totally convincing (sensors tend to be even too sensitive and not only record the displacements).

References

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3.1.1.8 Gas concentration

Why measure gas concentration?
This document describes techniques to monitor the concentration of gases in a radwaste repository environment (buffer, backfill, near field). Construction, operation and closure of a repository will cause to alter the usually initially saturated state of the geological environment resulting in the presence of gases due to different causes.

We will first list the different types of gases relevant in a repository. Next, the environmental conditions (unsatured versus saturated, gas state versus liquid state,…) in which the gas concentrations are to be monitored, are discussed. The main part will list the different techniques that are used – or have potential – for monitoring the gas concentration. We focus on techniques that can be used in site.

Concepts and definitionsy
The different gases that can influence the performance of a repository are.
- Air (N_2/O_2): due to construction works, the excavated areas consist initially of air; the air will also diffuse in the host rock near field; upon closure, the oxygen is consumed and the environment evolves from an oxic to an anoxic state;
- Hydrogen (H_2): produced by the anaerobic corrosion of metals;
- Methane (CH_4): may be generated by the anaerobic fermentation of organic matter;
- Carbon dioxide (CO_2): important component in the geochemical equilibrium of carbonate-rich porewater; may also be released from organic matter upon heating;

Two main phases can be distinguished: "free" gases and dissolved gases (normally in water). The dissolution of gases in water is usually limited – when the concentration exceeds a certain value, gas bubbles are formed. To measure gases present (dissolved) in water, different membrane designs have been developed for incorporating in sensors (e.g. in marine environments).

Techniques

- Sensors for multiple gases

A widely used technique for the gas monitoring is gas chromatography (GC). This technique allows both an analysis (which gases are present) and determination of the concentration of gases in a gas sample. Because of the physical dimensions of the device (even with the development of μGC based on MEMS technology) this technique is not really suitable for in situ applications. The current applications typically employ a filter to collect the pore fluid (or gas) in the medium, and which is connected with the analysis system at an accessible location.

Another sensing technique is based on non-dispersive infra-red (NDIR) spectroscopy. It is based on the fact that most gases have unique IR absorption signatures in the 2 to 14 μm region. A simple NDIR sensor consists of an IR light source, a sample chamber, an optical filter and an IR detector. By adding additional optical filters and detectors, multiple gases can be monitored.

- Specific gas sensors

Chemical reaction gas sensors (electrochemical and catalytic)

Concentration of hydrogen

- adsorption on palladium (Pd) forming a Pd-hydride; this phenomenon is used in several sensor designs, both optical (exploiting changing reflective or refractive properties) as well as electronic (e.g. thick film – resistance of the hydride is larger than the metal, and Schottky diodes where Pd is present in the junction, changing the energy barrier).

Concentration of oxygen

- optical (photoluminescence quenching using a ruthenium compound to measure O_2 partial pressure) (Ocean Optics: temperature influence, 1 year calibration); compound is contained in a gel at the end of an optical fibre so that the changing optical characteristics can be determined optically.

Concentration of methane

- NDIR
- Schottky junction (catalytic) based on ZnO

Concentration of CO_2

- most often used principle is NDIR;
- chemical sensors have sensitive layers based on polymer- or heteropolysiloxane: very low energy consumption and suited for miniaturisation; however more sensitive to drift and a lower lifetime.

References of use in previous experiences

Illustrative examples about the measure of gases in radwaste repository are given by the works done under FEBEX project [68] or HE-B [69]

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3.1.1.9 Gas pressure

Why measure gas pressure?
Several potential sources of gases in a repository have been identified: anaerobic corrosion of metals, degradation of the waste, generation by gamma radiolysis, and alpha-decay of the actinides [70].

Of all the gases potentially generated, hydrogen is certainly the gas which can be released in the largest amount. Different phenomena are associated with the generation of gas: chemical reaction, diffusion, two-phase flow and the creation of preferential pathways.

In a saturated environment, gas is dissolved in water as long as the solubility limit is not exceeded. When the rate of production however is such that the mechanisms of advection and dispersion (including diffusion) are too slow to transport the gas molecules away from the source, then the solubility limit will be exceeded and a distinct gas phase will form [71].

Initially, depending on the repository concept, parts of the repository are not saturated and gas is simply present as a distinct phase. Considering unsaturated granular materials (soils), both gas and water is present in the pores. Because of surface tension effects in the bubbles of air, the pore air pressure will be considerably higher than the pore water pressure. Depending on the pore size of the soil, a certain pressure can be sustained between the saturated medium and the unsaturated medium before gas will enter – this is called the air entry value of the soil. As explained in the next section, it depends on the sensor construction which value will be measured.

Techniques
In principle, gas pressure is a physical quantity that has been measured for a long time, and for which many principles have been developed. Most principles used today in pressure transducers are based on the deformation of a surface (membrane or diaphragm). The deformation is measured through deformation gauges, which convert the deformation into signal – usually an electrical signal, but also pneumatic, hydraulic and optical sensor signals are possible. The conversion mechanisms are basically the same as those of the other pressure sensors (total and hydraulic pressure). Similar performance criteria apply: long-term reliability, limited drift at long-term, well-characterised temperature sensitivity.

A gas pressure sensor typically contains one or two gas pressure inlet ports. This depends on the sensor type:

1. an absolute pressure sensor measures the pressure compared to vacuum and as such only needs one inlet port; one side of the pressure sensitive surface is then put under vacuum at the time of production; sometimes, this closed volume is filled with an inert gas so that a

"sealed" sensor is obtained – this might affect however the thermal sensitivity (thermal expansion of the gas);

2. a relative sensor measures the pressure compared to the ambient pressure; a second inlet is then connected with the ambient air (e.g. through a tube incorporated in the signal cable); care must be taken that e.g. ambient moisture will not affect this sensor;
3. a differential sensor measures the pressure difference between the two inlet ports; the difference with the previous sensor is that both pressure inlets are designed to carry process media (e.g. liquids); this sensor is typically used e.g. in air conditioning units or orifice type flow rate meters.

Depending on the application conditions, these inlet ports can be protected or not. In the most basic option, where it can be assumed that no other media than gas will be present, the membrane can be simply exposed to the environment.

In a repository context however, the inlet pressure port(s) need some protection against soil or rock material. Similar to hydraulic sensors, filters are used. While a mesh type of fabric will do to protect against dust, soil or rock embedded sensors are typically equipped with a filter tip (sintered steel, ceramic or plastic) enclosing a filter cavity. The pore size of the filters determines the sensor response in unsaturated soils.

If the pore size of a piezometer filter is large, then both air and water can freely pass into the chamber within the tip. If small pores are used however, water will pass through the filter but the air will require a considerable pressure difference before it can penetrate the pores. This pressure difference between the inside and outside of the ceramic, at which air will pass through, is termed the air entry value. If a low air entry value ceramic is used then the pore air pressure will be recorded, but when a high air entry ceramic is installed, it will be possible to record pore water pressure, so long as the difference between the pore air pressure and the pore water pressure does not exceed the air entry value. Typical values range from 5 kPa for large pore sizes (50 μ filters) to 100 kPa for 1 μ filters. Field experience however shows [72] that in the case of gas production due to organic decomposition (e.g. in peat soil), gas could also enter in a piezometer cavity through diffusion. Finally, it will convert there into a distinct phase which shows up as a sudden pressure increase in a piezometer. When long-term measurements of gas are therefore required, these will not be influenced significantly by the type of filter.

The most reliable way of measuring pore pressures, be it pore water or pore gas, is the use of piezometers which allow access to the filter cavity. This can be performed through the use of twin-tube piezometers (cf. section on porewater pressure), or of piezometers with otherwise flushable filters [73]. This increase in reliability requires however a more active interaction with the sensor, so that it is rather restricted to the operational phase of the repository (prior to closure).

Conclusion

In a repository context, both water pressure (optionally also suction) and gas pressure are typically of interest. It is important to consider both phases and all related phenomena (hydration, gas generation …) into one integrated monitoring programme, as the sensors of interest (piezometers) typically will be used for both parameters.

References of use in previous experiences

Same examples given for the measure of gases in radwaste repository, FEBEX project [68] or HE-B [69], are valid for gas pressure measurement as well.

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3.1.1.10 pH/Eh

Why measure pH and Eh?
pH and Eh are characteristic quantities describing the geochemical conditions, which determine chemical equilibrium and hence several processes, including

- Speciation of radionuclides (determining on their turn the migration process through diffusion, advection, …);
- Interaction of geosphere with engineered barriers and interaction between EB components (corrosion, leaching, dissolution, …).

pH and Eh are often interconnected; e.g. at the interface between the regions where oxic respectively anoxic conditions prevail (= the redox boundary layer), a steep pH gradient is present.

In waste repository conditions, knowledge of these parameters is essential when monitoring the evolution during operation and after closure. Applications include e.g. prediction or verification of corrosion rates (glass, metals, …) of the containment materials - and associated gas production.

Concepts and definitions
pH is a measure of the acidity or basicity of an aqueous solution. It approximates the negative logarithm (base 10) of the molar concentration of dissolved hydronium ions (H_3O^+). It is an approximation as pH takes into account an activity factor. This factor represents the tendency of hydrogen ions to interact with other components of the solution, which affects among other things the electrical potential read using a pH meter.

Hydrogen ion activity coefficients cannot be measured directly. Therefore, the pH scale is defined in practice as traceable to a set of standard solutions whose pH is established by international agreement.

Techniques [74]
The most widely used tool for pH detection is the glass electrode first described in the first decades of the 20th century [75]. This potentiometric electrode usually consists of a Ag^+/AgCl working electrode immersed in an internal KCl buffer solution with defined pH and a Ag^+/AgCl

reference electrode. It exploits the potential difference establishing in the proton-selective glass membrane separating the internal buffer solution and the external test solution as a measure for the proton activity in the sample. Ion-selective field effect transistors (ISFETs) on the basis of metal oxide screen field effect transistor (MOSFET) technology offer an alternative in fields where the risk of breakage limits the use of glass electrodes. Lately an iridium oxide-based electrode has been reported with good stability even in strongly alkaline solutions or samples containing hydrofluoric acid, which normally cause errors or irreversibly damage the ion selective membranes of glass electrodes, ISFETs or other metal oxide electrodes. pH electrodes show a linear (Nernstian) response towards pH allowing a fast two-point calibration and they usually feature a wide working range (ca. pH 2 - pH 12).

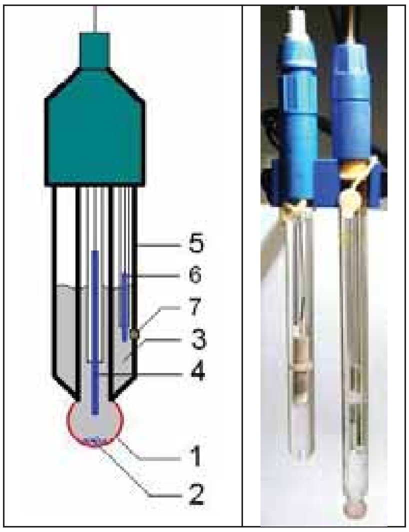

Figure 47: (left) Schematic view of a pH glass electrode, with (1) ion-sensitive glass membrane, (2) sometimes some AgCl precipitation, (3) internal solution, usually 0.1M HCl for pH electrodes, (4) internal electrode, usually AgCl or calomel, (5) sensor body, made from non-conductive glass or plastics, (6) reference electrode, usually the same type as (4), and (7) junction with solution under investigation, usually made from ceramics or capillary; (right): couple of glass-electrodes – left an AgCl reference electrode, right a pH glass electrode.

However, there are also several drawbacks, which make the use of pH electrodes difficult or even impossible for certain applications. Measurements with electrodes can generally be biased by electromagnetic fields, changing flow velocity of the test solution or solutes such as heavy metals, proteins or hydrogen sulfide. ISFET and metal/metal oxide electrodes are cross-sensitive towards redox changes in the sample. During long-term measurements small variations of pH are difficult to observe, since the electrode signal drifts with time. The dependence of the liquid junction potential on the composition and concentration of the sample can be a further source of error. pH detection in small sample volumes or high resolution pH detection in heterogeneous systems requires miniaturisation of the working electrode and sometimes also the reference electrode, which involves complex fabrication procedures.

Experiences and results

- Application in underground research labs − HADES lab (Mol, Belgium) [77]

pH (and Eh) measurements in HADES are based on clay water retrieved from piezometer filters (twin tube system, pumped in loop). Originally, the Xerolyt^{TM} electrodes from Mettler (type HA405-DXK-S8/120) were used. Xerolyt^{TM} is a solid polymer containing KCl. It allows for higher pressures (up to 1.6 MPa at 25°C, down to 5 bars at 100°C) – and there is no need for a ceramic or capillary junction (item 7 in Figure 47) – and open junction is possible. They appear to leach however KCl, while bacteria seem to like the Xerolyt itself.

Currently, the InPro 4800SG electrodes (also from Mettler) are used. Also here KCl leakage is an issue. This requires that rinsing or purging of the measurement circuit is required prior to performing calibration and measurements.

Continuous measurements on clay are therefore not possible with this type of sensors.

Optical chemical pH sensors overcome many of these problems and can therefore provide an alternative to electrochemical pH sensors. In their most simple version, they exist as pH indicator strips, where the colour change is an indication of the pH. Optical sensors (not requiring a human intervention) generally comprise a light source (e.g., xenon lamp, light emitting diode (LED), laser diode, laser), a detector (e.g., photodiode, photomultiplier tube (PMT), CCD-chip) and the sensing element (= optode) responsible for the selective analyte recognition and signal transduction. In case of optical pH sensors this optode is usually composed of an indicator dye immobilised in a proton-permeable polymer matrix by covalent coupling, adsorption or entrapment. pH indicators are weak acids or bases, which reversibly alter their optical properties (e.g., absorbance, fluorescence intensity) upon protonation/deprotonation.

The majority of pH optodes found in literature are fluorescence-based due to the higher sensitivity of the resulting sensors, the low indicator concentrations required and a less complex measurement set-up (no light transmission through the analyte necessary, excitation and signal read-out from one side of the sensor membrane).

Since optical pH sensors measure the proton concentration and not the activity they are cross-sensitive towards the ionic strength of the sample, which has to be corrected. This influence, however, can be minimised by the selection of suitable indicator and sensor polymer combinations. The polymer matrix has a strong impact on the characteristics of the pH optode. The microenvironment in the polymer can induce a shift of the apparent pKa (pKa') of the indicator by stabilising its protonated or deprotonated form. Optical pH sensors composed of a pH indicator, which is electrostatically immobilised on commercial ion exchangers or entrapped in hydrophobic plasticised PVC have been reported. Sol-gel glasses are a further intensively investigated pH sensor matrix. However, one of the disadvantages of these approaches is slow response and/or recovery times. Additionally, plasticised PVC membranes are not stable since the plasticiser leaches from the membrane with time thereby changing the characteristics of the pH sensor. The preparation of intact solgel membranes is time-consuming and difficult and sol-gel-based optodes show a poor reproducibility.

In contrast to electrochemical sensors pH optodes show a sigmoid response towards pH and the dynamic range is usually limited to ca. pKa' ± 1.5. Yet, the small dynamic range results in a high signal change with pH and therefore in a high sensor resolution. Furthermore, a sensor working range of ca. 3 pH units is sufficient for many analytical problems. Within the pH range of ca. pKa' ± 0.5 the optode response is quasi-linear, which can be exploited for a fast two-point calibration provided that only small pH changes are to be detected. A signal drift like in the case of pH electrodes can be avoided by applying referenced measurement schemes instead of measuring the absorbance or fluorescence intensity.

Field experiences with autonomous chemical sensors (including pH) are reported by the marine and aquatic chemistry communities [75]. Field application usually also involves miniaturisation.

Apart from glass electrodes, also LIX-based pH microelectrodes (liquid ion-exchange incorporated in PVC acting as the proton selective membrane) have been developed. pH microelectrodes have been fabricated with tip diameters < 20 μ. Microelectrodes are however very expensive, they do not always feature optimal measurement properties and they are also extremely fragile, limiting their use in field applications especially at elevated hydrostatic pressures. The current opinion is that optical methods are preferred over the glass electrodes because of their higher signal stability and robustness (operation under high hydrostatic pressures). In situ pH measurements using spectrophotometric procedures are now being made on an experimental basis.

Current developments regarding optical sensors involve planar sensors (based on CCD-imaging chips, allowing the measurement of the spatial distribution on a small area) and dual sensors, where two (sometimes coupled) parameters – e.g. pH and pO_2 – are monitored through one sensor by applying two sensitive dyes (each packaged separately) to the sensitive surfaces [74].

Challenges for in situ application in repositories
In situ chemical sensing is not employed as extensively as physical sensing due to the analytical challenge in making autonomous chemical measurements in natural environments with complex background matrices against which low analyte concentrations must be detected. In the lab, these analytical challenges can be overcome through the use of very sophisticated instrumentation. These complex measurements often involve several analytical steps. In situ chemical sensors or analysers that can be deployed for long time periods require much simpler and more robust methods of chemical analysis.

A major challenge encountered in the field is (bio) fouling of sensor or analyser surfaces – e.g. due to growth of micro-organisms on the sensitive surfaces. In repository conditions, this might be a potential issue during the operational phases – up to some time after closure – as biological phenomena could be significant (e.g. sulphate reducing bacteria could enhance corrosion). On the other hand, combinations of organisms or biologically active substances (e.g. enzymes) with these sensing surfaces are currently being investigated in the context of biosensing. The potential of this approach for repository applications is still to be assessed.

Commercial implementations
Ocean Optics [76]: optical pH and pO2 sensors

- indicator materials embedded in sol-gel matrix
- sol-gel matrix made up of silica, ethanol and water; the matrix pore size is controlled so that the embedded indicator dye does not leach out
- transducer materials include both fluorescence-based and absorbance-based indicators
- the colorimetric change is detected by a spectrometer

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3.1.1.11 Colloids

Why monitor colloids?

Colloids are natural and ubiquitous in groundwater and may also be generated by physical and chemical processes resulting from the presence of a geological repository for radioactive waste. In many repository designs, the high-level waste is packed in massive metal canisters which are surrounded by a large volume of bentonite clay, all of which constitute the engineered barrier system. The canisters will slowly degrade and eventually fail, releasing some radionuclides, most of which are expected to be retained and to decay within the bentonite.

Although bentonite is expected to act as a colloid filter, the outer surface of the bentonite may itself act as a source of colloids due, for example, to erosion by flowing water in host rock fractures. For these colloids to have any effect on radionuclide transport in the host rock, the radionuclides in question must be able (i), to migrate to the bentonite/host rock interface before they decay, and (ii) subsequently sorb on the bentonite colloids that are generated there. If the bentonite barrier operates as expected, transport of any sorbing radionuclides will be slow and the above conditions are unlikely to be met for most safety-relevant radionuclides. There are, however, conceivable scenarios that would allow more rapid transport of some sorbing radionuclides through the bentonite barrier, including, for example, the creation of temporary flow paths through the bentonite by repository produced gas (from canister corrosion etc [78], [79]).

The impact of natural groundwater colloids on transport is also a concern in the case of fractured hard rocks.

Due to a lack of relevant in situ data on colloid and colloid-mediated radionuclide transport, most performance assessment (PA) studies treat such scenarios conservatively (or overconservatively).

Techniques: the use of tracers

Tracers are used to gain knowledge on the in-situ retardation of colloid associated, safety relevant radionuclides.

Tracers are unique or highly indicative chemical species, for their colour, radioactivity, or other distinctive property, which can be introduced into a system and followed to “fingerprint” an element of interest, distinguishing it from other sources. In addition, tracers can be used to determine and understand the flow path of fluids. The occurrence of artificial tracers, for example perfluorocarbon tracers (PFTs) or SF6 in natural systems is so small that detection and attribution may be done at parts-per-billion detection.

Chemical tracers, both natural and introduced, can be used for in situ subsurface characterization, model calibration and leak detection. Naturally occurring chemical constituents, such as stable isotopes of C, H, O, N, or sulphur (S); noble gases Kr, Ne, Ar, He, Xe and their isotopes; and radioactive isotopes (e.g., 3H, 14C, 36Cl, 125I, 129I, 131I), can be used to assess fluid origin, detect migration or leakage into the atmosphere and assess interaction with host rocks along flow paths [80]. A variety of sampling and analytical approaches are available, including direct extraction from flux chambers, simple or complex soil gas wells, and sorbent approaches. Analysis can be done in the laboratory or via various types of field instruments. Research funded by DOE’s Core R&D program has led to the development of an in situ stable isotope analysis system as part of a focus at developing novel monitoring tools for geologic sequestration. Phase-partitioning tracers could be used to determine the amount of immobile phases (such as the residual oil in a petroleum reservoir). Preliminary tests have been carried out at the Frio project in Texas [78] to test the applicability of phase-partitioning tracers to estimate the amount of residual gas trapping that has taken place. Residual gas trapping is an important parameter for estimating long-term storage integrity.

It is a proven technique in many applications. In advanced applications (for assessing a potential leak), tracers can provide essential information about flow path and processes that could be used to design effective remediation.

Many introduced tracers (PFTs, SF6) in water and ecosystems are powerful greenhouse gasses. Therefore, they need to be used conservatively. Because of low detection limits, contamination is a serious risk; it is important to use best practices to inject tracers (separate handling for injection and detection). More information is needed about interaction of introduced tracers with water rocks, soil and organics. Natural tracers are known to have complex reactions with rock, water, and soil, requiring a fairly sophisticated approach to produce a correct interpretation.

References of use in previous experiences

The Colloid and Radionuclide Retardation Experiment (CRR) is dedicated to improve the understanding of the in situ retardation of colloid-associated, safety-relevant actinides and fission products in the vicinity of the Engineered Barrier System (EBS)/host rock interface [81]. In addition to a series of in situ dipole experiments that were carried out at the Grimsel Test Site (GTS), the project partners, namely ANDRA (F), ENRESA (E), FZK-INE (D), JNC (J), USDOE/Sandia (USA) and Nagra (CH), funded an extensive programme of laboratory and modelling investigations. The aims of CRR were: examination of the in situ migration of bentonite colloids in fractured rocks, investigation of the interactions between safety relevant radionuclides and bentonite colloids in the laboratory and in situ and, in addition, testing of the applicability of numerical codes for representing colloid-mediated radionuclide transport.

The central part of the CRR project was a series of dipole tracer tests that were carried out in a well-defined shear zone, in which dipole flow fields of 2.2 and 5 m length were generated. Preliminary tracer tests were performed with uranine, followed by tests with bentonite colloids and homologue elements for the tri- and tetravalent actinides (Tb for Am, Hf and Th for Pu, respectively). The tests culminated in the injection of the final tracer cocktails containing different isotopes of Am, Np, Pu, U, Tc, Th, Cs, Sr and I in the absence and presence of bentonite colloids.

The field installations consisted of several on-line measurement devices such as a downhole uranine detection device for the determination of the tracer input functions, a High Purity Germanium (HPGe) detector for γ-spectrometric measurements as well as a Laser Induced Breakdown Detector (LIBD) and a Photon Correlation Spectroscopy (PCS) apparatus for on-site colloid detection. The analytical techniques that were used off-site consisted of α-/γ-spectrometry and ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) measurements for radionuclide detection as well as of Single Particle Counting (SPC) for the determination of the different colloid size classes. The interaction of the strongly sorbing tri- and tetravalent actinides with the equipment was avoided by producing as many as possible of those parts of the in situ equipment that were in direct contact with the tracers in PEEK (an inert plastic).

The natural colloid background of the groundwater in the experimental shear zone showed an average colloid diameter around 200 nm and a stable colloid concentration around 5 μgL^{-1}.

Increased colloid concentrations observed temporarily at the beginning of the experiments were most likely due to mechanical stress induced by pressure pulses generated during installation of the test setup. The four different colloid detection techniques, namely LIBD, ICP-MS1, PCS and SPC, produced internally consistent breakthrough data of the injected bentonite colloids.

The bentonite colloids arrived slightly earlier than did the conservative dye uranine and the recovery was about 90%. Filtration effects varied depending on the colloid size and measurement technique employed and, as such, they require further investigation.

Homologue pre-tests proved to be very useful for the prediction of the in situ behaviour of tri and tetravalent actinides. In the absence of bentonite colloids, a clearly lower recovery was found for the homologues than when injected together with bentonite colloids and the peak maxima of the homologue breakthrough were slightly shifted to earlier arrival times compared to that of the uranine.

The tracer cocktail composition for the final tracer injections covered the entire range of oxidation states from -I to VI and was decided based on the results of laboratory experiments, the kinetics of redox reactions and practical constraints on the in situ use of these elements. The preparation of an injection cocktail which contains tri- and tetravalent actinides proved to be problematic, as shown by the presence of a variable colloidal fraction for Am, Pu and Th, even in the absence of bentonite colloids. However, the injection cocktail, which included bentonite colloids, showed high colloid association and long term stability for the tri- and tetravalent actinides with the bentonite colloids, indicating that a significant proportion of the radionuclides were associated with the added bentonite colloids.

In the first run (without bentonite colloids), the tri- and tetravalent actinides Am, Th and Pu displayed lower recovery, less tailing and a peak time which was about 10 minutes earlier than U, Np and I (which is assumed to behave in a conservative fashion), indicating that a fraction of these actinides was transported in a colloidal state. With regard to the varying colloid content in the injection cocktail, the source of these colloids cannot yet be uniquely defined (homogeneous- or heterogeneous radiocolloids) and artifacts, for example, during cocktail preparation, cannot yet be ruled out completely.

With the addition of bentonite colloids, an increased recovery of Am, Pu and Th compared to the first run was observed. The shape of the breakthrough curves did not change significantly as the peak in the first experiment was also affected by a colloidal fraction. Only about 1% of the Cs was colloidally transported which implies that 90% of the initially colloid bound Cs in the injection cocktail (10% Cs in the injection cocktail was in colloidal form) desorbed during migration.

As conclusions of the research, it was stated that the following five requirements must be fulfilled in order that colloid-facilitated transport of radionuclides in a potential repository host rock would be of significance to the long-term performance of a waste repository [82]: Colloids must be: present, mobile and stable under the given groundwater conditions (geochemical and hydrogeological environment), radionuclide association with the colloids must take place and the association must be irreversible. Therefore the first outcomes of the CRR experiment are related to these five fundamental questions.

- *Presence*: natural colloids are, in principle, present in every natural groundwater. CRR concentrated on the investigation of the potential formation of bentonite colloids at the bentonite/host rock interface. Colloids were formed in the laboratory under dynamic and quasi-stagnant groundwater conditions, implying that colloids may be produced even in the absence of strong erosional forces. The concentration of colloidal material generated at the interface was observed to increase with increasing water flow.

- *Mobility*: the injected bentonite colloids travelled along a 2.23 m dipole flow field in the experimental zone. The recovery of conservative tracers was 100 % at the given flow rates. Colloid recovery calculations were carried out with data from a range of measurement techniques and preliminary results suggest that 80 to 90 % of the colloids passed through the test shear zone with little significant retardation.

- *Stability*: as expected from the study of other groundwater systems, it was confirmed that colloid stability is strongly dependent on the pH and Ionic strength (I) of the groundwater type (see evolution of hydrodynamic diameters of colloids below).

  Therefore, bentonite colloids show high stability under the experimental groundwater conditions in the experimental site ($I = 10^{-3}$ M and pH = 9.5). In order to verify this, the colloid size distribution was also investigated for longer time periods with colloids obtained from previously washed bentonite and conditioned in the experimental site groundwater. The concentration of the suspension was approximately at 2000 mg/L. The colloid size distribution was found to be rather constant over a period of approximately five months.

- *Association*: the migration behaviour of the tri- and tetravalent actinides Am and Pu was strongly mediated by the bentonite colloids and recovery increased from 20-30 % in the absence of bentonite colloids, to about 60-80 % in the presence of bentonite colloids.

  Batch experiments and the high content of Am and Pu bound to the added bentonite colloids in the injection cocktail clearly display uptake of at least these elements on the bentonite colloids. The breakthrough curves below show that the colloids, the tri- and tetravalent actinides and the Cs arrived slightly earlier than the "conservative" solute.

- *Irreversibility*: under the given experimental conditions, an evaluation of the reversibility of radionuclide sorption onto bentonite colloids cannot be done in situ. However, CRR laboratory desorption kinetic experiments indicate that both Cs and U indicate some degree of irreversibility, implying that, at least part, of the radionuclides could potentially migrate through fractures in the host rock, provided the colloids remain stable and mobile.

Context of application within Repository Monitoring
Colloids monitoring could be of use in a repository to monitor bentonite buffer erosion in the contact with the host rock.

References of use in previous experiences
As already mentioned, the Colloid and Radionuclide Retardation Experiment (CRR) Project in the Grimsel Test Site.

Limitations
Basically there are no sensors available to carry out online measurements of colloids in a repository, so any measurement involves taking samples.

Further developments
The obvious development in this case would be the construction of sensors for online measurements.

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3.1.2 Fibre Optic Sensors

Given the size of the foreseen repositories (in the kilometer range) and the number of cells to monitor (several tens), the corresponding number of required sensors to perform efficient monitoring would rapidly become a limitation, especially if the sensors are wire-connected.
Optical fibre sensors (OFS) are an exceptional tool for their multiplexing ability and their reduced size. Detailed state-of the art can be found in [83] or [84]. The current description focuses on sensors that may be of major interest for geological repositories.

Following a series of rudimentary descriptions of fibre optic technology, a brief description of the history of OFS is proposed. Then, a state-of-the-art of strain OFS currently used in civil engineering will be presented. Chemical OFS will also be described. A final part is dedicated to radiation OFS.

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3.1.2.1 Optical fibres and related sensors: back to basics

Optical fibres
An optical fibre [85] is a waveguide the size of a single hair (0.1 mm) that enables conveying light, i.e. an electromagnetic wave with frequencies on the order of 100 THz. The breakthrough of this technology occurred in the 1970's when lasers were associated with optical fibres. A wide

array of optical fibres have been developed in either glass or plastic, with solid or hollow cores, packaged in very diverse shapes to convey signals that may be visible or invisible, usually with wavelength around 1µm. These various parameters are chosen depending on the specificities of the given application. For geological repositories, plastic optical fibre [86] will not be considered because it suffers from short lifetimes and does not endure radiations; low-cost and large deformations are its great advantages.

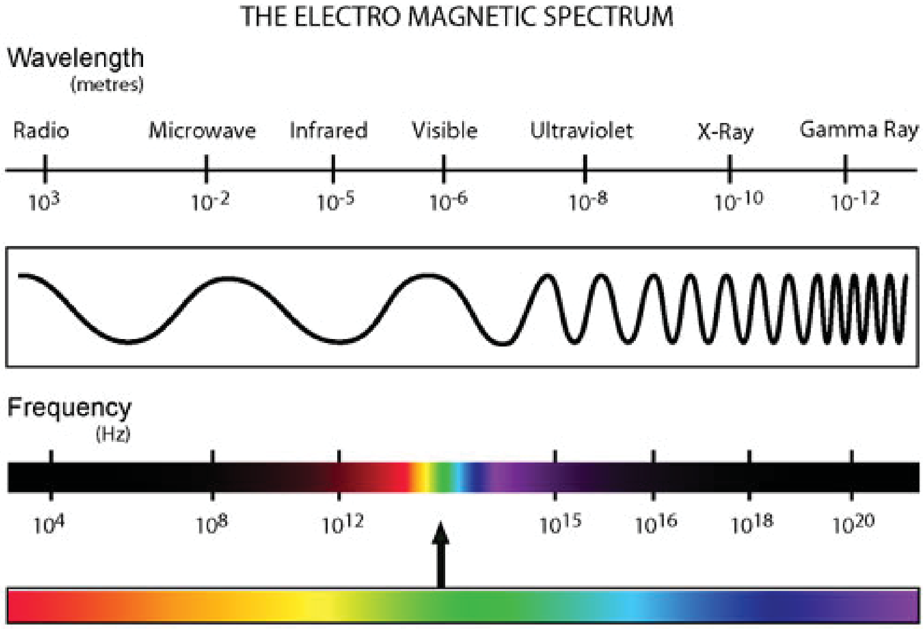

Figure 48: The electromagnetic spectrum: optical fibres convey visible and near infrared light

To ensure guiding, the optical fibre is made of a cladding and a core, generally composed of the same material. Included impurities called dopants (such as Ge, F…) modify the refractive indexes. When the cladding has a lower refractive index, light is kept in the core by total internal reflection as sketched in Figure 49.

Depending on the refractive index difference, on the size of the core and the working wavelength, many or only one propagation paths (modes) are supported inside the fibre, either called multi-mode fibres (MMF) or single-mode fibres (SMF). Multi-mode fibres generally have a larger core diameter, in the order or 50µm, can handle high power but propagation losses are higher. The most common type of single-mode fibre is called G.652, a code from the ITU-T (Int'l Telecommunication Union). It is designed for use in the near infrared. It has a core diameter in the order of 10µm, a refractive index difference in the order of a few 10^{-3}; propagation losses may be as low as 0.2dB/km if used at 1550nm.

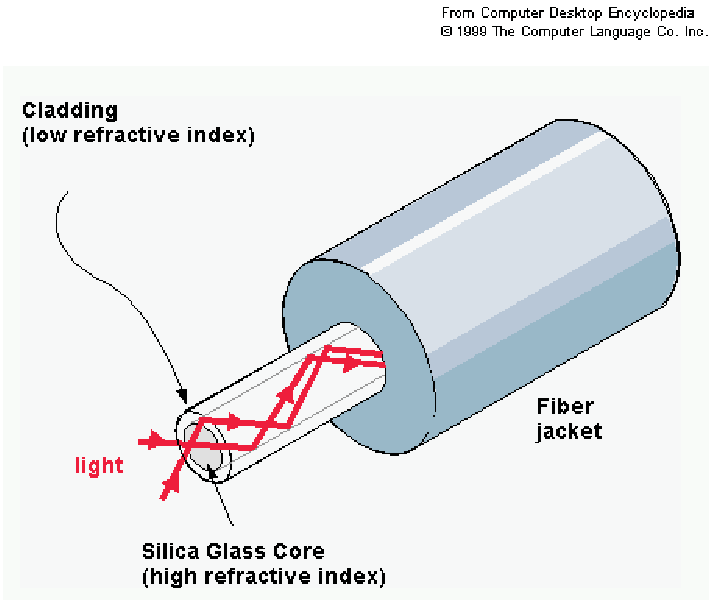

Figure 49: Structure of a silica optical fibre

Related specificities of optical fibre sensors

From these characteristics, a number of specificities regarding fibre optic sensors (or OFS) can be stated:

- As opposed to electronic sensors, an optical fibre does not radiate. The electromagnetic parasites that limit the dimensions of coaxial cables connecting conventional sensors along with any lightning risk are thereby eliminated.
- Since glass exhibits a very high melting point, OFS may be applied with very high temperature settings. These sensors also resist very high pressures, even in the presence of ionizing radiation. However, the protective envelope (fibre jacket) depicted in Figure 49, which proves critical to the effective mechanical resistance of silica, must be chosen on the basis of actual use conditions: standard acrylate does not withstand high temperature. Moreover, some specific internal treatments, such as Bragg grating inscription (which gets deleted beyond a temperature of 300°C), may constrain the actual range of application.
- Dimensions are very small (millimeter scale), OFS are attractive for integration into other structures ("smart structures"). A disadvantage of this specificity is that optical fibres are quite fragile and need additional protection to perform reliably in field set-up's.
- Signal propagation losses are extremely low: as stated before, if losses lie below 5% per kilometer of propagation, a signal can propagate over several kilometers without practically any distortion. This characteristic becomes essential when remotely interrogating sensors placed inside inaccessible zones, such as radioactive wastes storage cells, which enables the upgrade of the optoelectronics during long exploitation periods and reduces the specification for very-long lasting monitoring system.
- The OFS family of sensors displays a greater level of sensitivity and dynamic than conventional sensors, while maintaining relative resolutions on the order of the wavelength, i.e. 10^{-6} m, thanks to the interferometric setups.
- Since the bandwidth generated from telecommunications transmissions is extremely broad, multiplexing capabilities are significant: tens of sensors placed on the same optical fibre can all be read simultaneously as long as the corresponding spectral ranges remain offset within the silica transmission window, 0.8 µm-1.7 µm. The sensor grating created in this manner makes it possible to anticipate a sizable measurement cost reduction, provided that the measurement system and optoelectronic demultiplexing constitute basic components in the instrumentation pricing. Furthermore, such an architecture provides the user with data from each sensor in homogeneous form, which allows data fusion to become intrinsic. OFS thus

leads to optimized instrumentation systems. Also, sensor signal acquisition speeds are solely limited by the electronic sensor interrogation system.

However, given that the useful signal is propagating over the 10 µm (0.01 mm) central axes of the typical single-mode optical fibre, the connections between fibre segments offer sensitive points that simple dust is able to degrade; this aspect necessitates extreme care during any handling. With this consideration in mind, the majority of connections are routed far from construction site conditions. An alternative solution calls for the use of multimode optical fibres, yet restricting the sensing possibilities. Indeed, Bragg gratings or Brillouin scattering for instance are limited to single-mode fibres, as described in the following.

Extrinsic versus intrinsic sensors

In general, optical fibre sensors are classified as intrinsic or extrinsic type. In the extrinsic type of sensor shown in Figure 50 (a), the optical fibre is only used as a means of light transport to an external sensing system i.e. the fibre structure is not modified in any way for the sensing function.

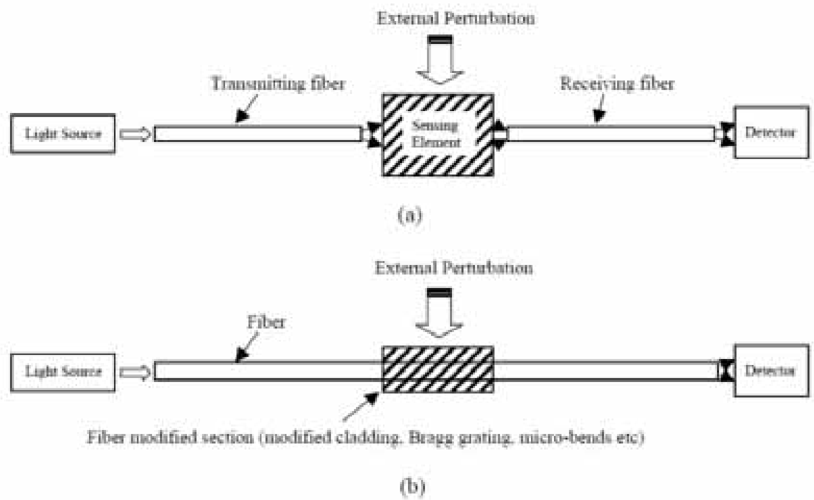

Figure 50: Schematic showing the general design scheme of (a) extrinsic (b) intrinsic

By contrast, in intrinsic sensors, light does not have to leave the optical fibre to perform the sensing function: the fibre structure is modified so that the fibre itself plays an active role in the sensing function. Examples of intrinsic fibre sensors include Fibre Bragg gratings (see 3.1.2.6). Fabry-Pérot cavities (see 3.1.2.6) are an example of extrinsic sensor.

History of Optical fibre sensors

From a historical perspective, the first OFS *were* based on a study of intensity variations in a signal transmitted within a multimode optical fibre since the components required for such systems were the only ones available at reasonable cost.

The most basic measurement system, called *All-or-Nothing* (AON), consists of examining the propagation or non-propagation of light transmitted within the optical fibre, as diagrammed in Figure 51: the signal transmitted in an optical fibre undergoes a strong reduction to reach a near-zero value when the fibre breaks. These AON systems on OFS were implemented in order to monitor the state of a concrete tunnel as early as 1986 [87]. This type of sensor does not yield any information on either crack size or evolution over time. To overcome this limitation, the microbend type of sensor was developed [88]. As an optical fibre bends, a portion of the light is lost through the cladding at the exact point of bending. These losses can be accurately detected by measuring light intensity attenuation. A commercial implementation of microbent sensors is developed by the company OSMOS.

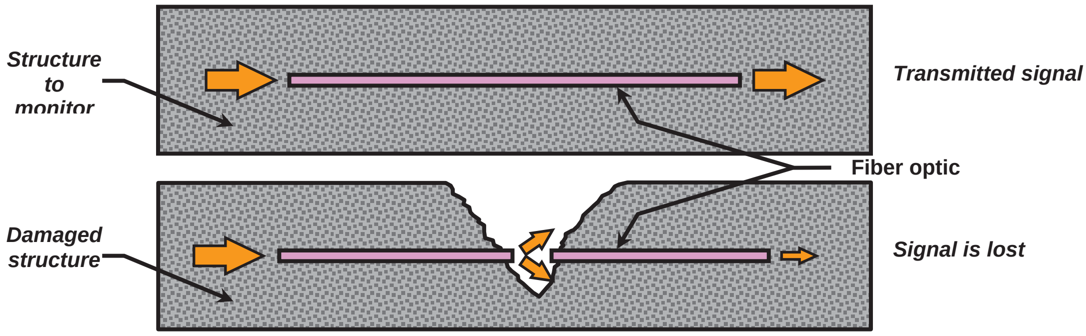

Figure 51: Principle behind fibre optic sensors with an AON system, ©James Dupont

While these sensors are remarkable by virtue of their simplicity and only require very inexpensive equipment, their major difficulty lies in generating a stable intensity reference. As a case in point, the slightest dust accumulating on sensor connectors partially obstructs light transmission, and the corresponding loss of light intensity then cannot be distinguished from the useful signals. A system devoid of connectors, where the links between optical fibres consist merely of splices, does not allow for any manipulation. Moreover, if the signal-transmitting optical fibres are exposed to partial degradation, e.g. by strong curvature at the interfaces (protruding concrete blocks) or by radioactive waste exposition, the signal intensity losses will also be interpreted as a significant evolution in the proportion of sensor-packed fibres. For this reason, the majority of OFS are now of the interferometric type.

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3.1.2.2 Temperature and Strain Interferometric fibre-optic sensors

At present, information coding is primarily interferometric. Three main families of interferometric strain OFS can be distinguished according to whether the measurement is local, integrated over cm-sized distances, or distributed (i.e. continuous along the optical fibre), as shown in Figure 52.

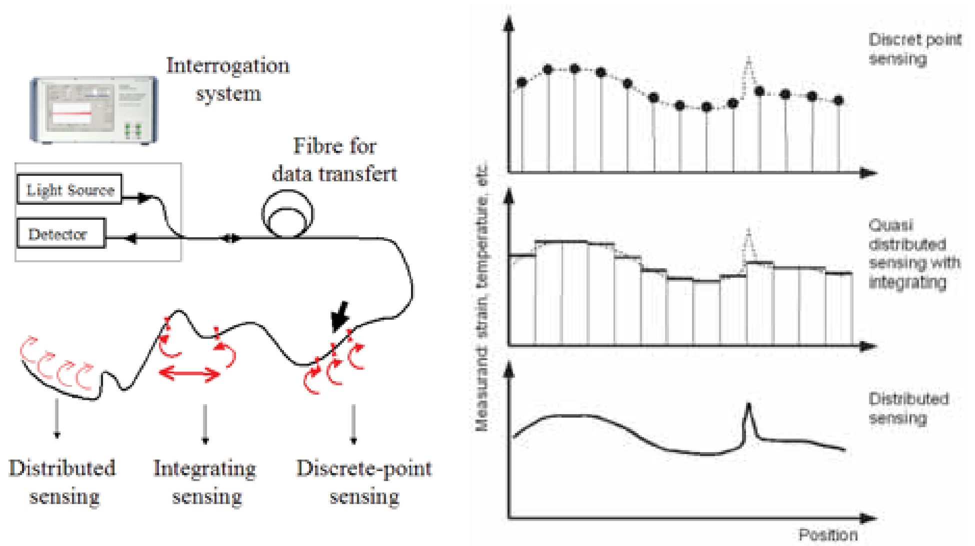

Figure 52: Diagram of a fibre-optic measurement system: An acquisition device is connected to an optical fibre containing sensors used to convey information. The sensors are local (red arrows), long-based (where the sensor corresponds to the distance between arrows), or distributed (where the fibre itself becomes a sensor)

Local optic strain sensors

Measurement is carried out at specific points, which are sites of special treatment, such as Fabry-Perot cavities or Bragg gratings.

<u>Fabry-Perot Principle</u>

Fabry-Perot sensors were among the first OFS available on the market [89]. A Fabry-Perot (FP) is an interferometer made of two partial mirrors facing each other. When light enters this cavity, a part is reflected, while the rest propagates towards the other mirror, where another partial reflection occurs. These different reflections induce an interference signal whose properties depend on the distance between the mirrors (among other parameters such as light coherence).

In its simplest form, the mirrors are deposited on the tips of multimode optical fibres and these fibres are spot fused into a capillary. As shown in Figure 53, the air gap between the mirrors is the Fabry-Perot cavity length and the distance separating the welded spots, the gage length, dictates the gage operating range and sensitivity. FP sensors are extrinsic OFS as the sensing element is not the fibre itself. The usual measurement technique is to reproduce a similar FP cavity inside the interrogation unit. The difference between the two optical cavity lengths induces interferences. More precisely, both cavities (or “arms” of the interferometer) are illuminated: when the lag time is zero, the interferences are constructive and an intensity peak is measured. As illustrated in Figure 53, the determination is absolute (and not to within 2π) given that the light source is set to be only slightly coherent. Beyond the source coherence, i.e. at a few µm, interference fringes become blurred (Figure 53).

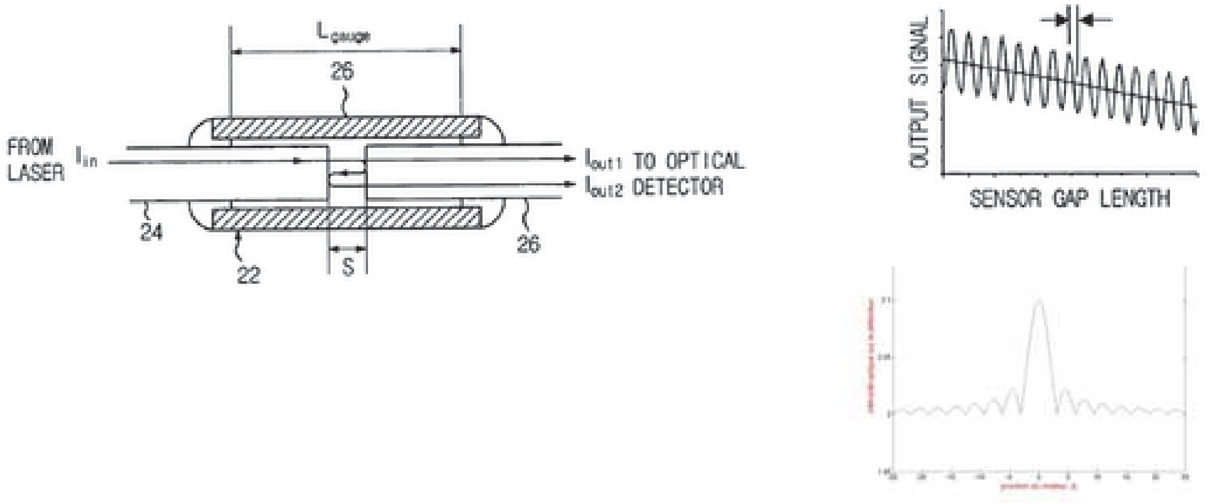

Figure 53: Transmission-type extrinsic Fabry-Perot interferometric optical fibre [90] and related output signal (up) if coherence light is illuminating the sensor (down) in case of low-coherence

Many sensors based on this principle are currently available for geotechnical monitoring, including piezometers, weldable and embedded strain gauges, temperature sensors, pressure sensors and displacement sensors. As an example, this technology has been installed for the monitoring of El Mauro dam located in Chile by RocTest company in 2005.

BRAGG grating principles

Bragg grating sensors are intrinsic OFS as the optical fibre constitutes the sensitive element. It consists of periodic modulation of the refractive index of the optical fibre core [91]. This pattern is usually sub-micrometer sized, yet repeated over several millimeters. This modulation may be obtained thanks to the photosensitivity of silica, whose atomic arrangement can be permanently modified by means of special lighting sequences (usually UV exposition).

Should this modulation be performed in accordance with a specific geometry called *Bragg grating*, it then displays a reflective power over a very narrow spectral bandwidth centered at wavelength λ_B, which is directly proportional to the pitch size Λ (≈ 0.5 µm) and the refractive index n ($\lambda_B = 2n \cdot \Lambda$). Any elongation or contraction thereby *displaces* λ_B, whose spectral monitoring enables determining the inductive phenomena. More precisely, the dependence of Bragg wavelength on temperature T, elongation ΔL and pressure P can be expressed as follows:

Equation 3.1.2-1

$$\frac{\Delta\lambda_B}{\lambda_B} = a\Delta T + b\frac{\Delta L}{L} + c\Delta P$$

where $a \approx 8 \cdot 10^{-6}$, $b \approx 0.8 \cdot 10^{-6}$ and $c \approx 3 \cdot 10^{-6}$ respectively, with ΔT expressed in °C, ΔL expressed in µm while L expressed in m and ΔP expressed in MPa.

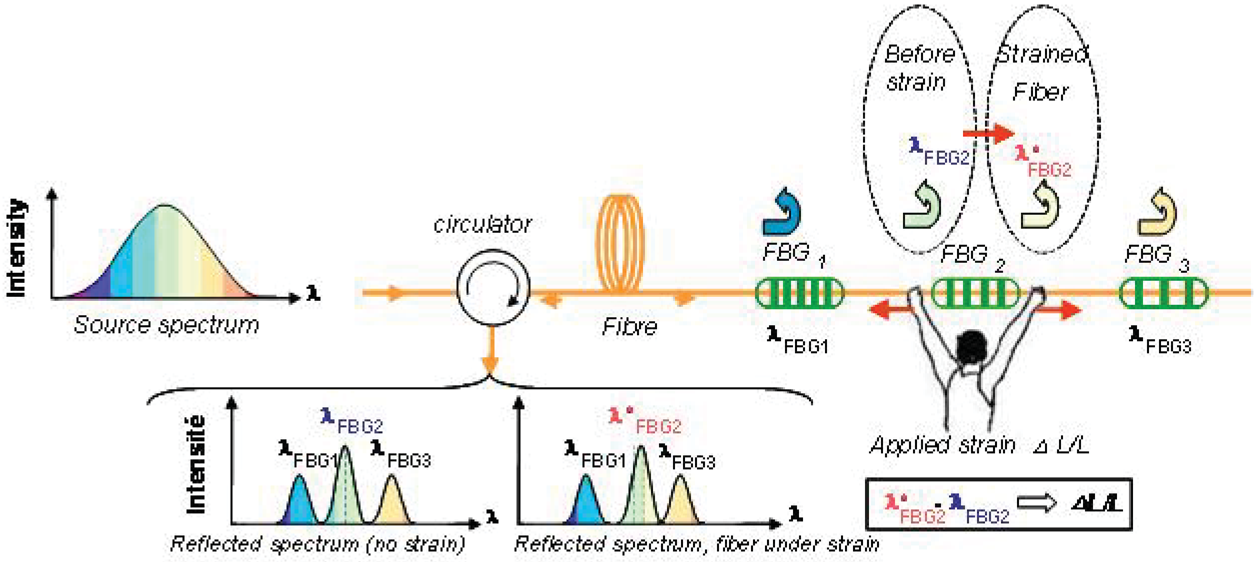

Figure 54: Bragg grating operating principle

Sensing Networks

As diagrammed in Figure 54, several Bragg gratings are easily multiplexed on the same optical fibre, regardless of the measurand, i.e. temperature or elongation (or chemical species as developed in 3.1.2.3). To proceed, it is simply necessary to sequence the gratings with a slightly different pitch Λ. The incident light is successively reflected at λ_{B1}, $\lambda_{B2,...}$, λ_{Bn} by the different gratings, and the spectral variations of these distinct wavelengths are analyzed by the instrument (spectral analyser) located at the fibre end.

One limitation with this set-up is that each sensor addresses a specific spectral window. According to Equation 3.1.2-1, variations of 70°C or 5000 µm/m - which represent the extreme values for civil engineering applications - correspond respectively to 1 nm and 6 nm. In order to avoid overlapping therefore, a 50-nm wide source can only illuminate 50 thermometers or eight strain sensors.

To increase multiplexing capabilities, several optical fibres configured in parallel can then be introduced. Figure 55 gives an overview of a possible sensing network with an interrogation system containing a multi-wavelength measuring device connected to different fibre optic sensors with a link to a computer. Such a device exists in laboratory packages, rackable-packages or ruggedized for field applications.

Price and size significantly depends on packaging, number of channels (which means integration of a switch or a multiplexer) and speed (up to the 1 kHz changing from a spectral to a temporal approach).

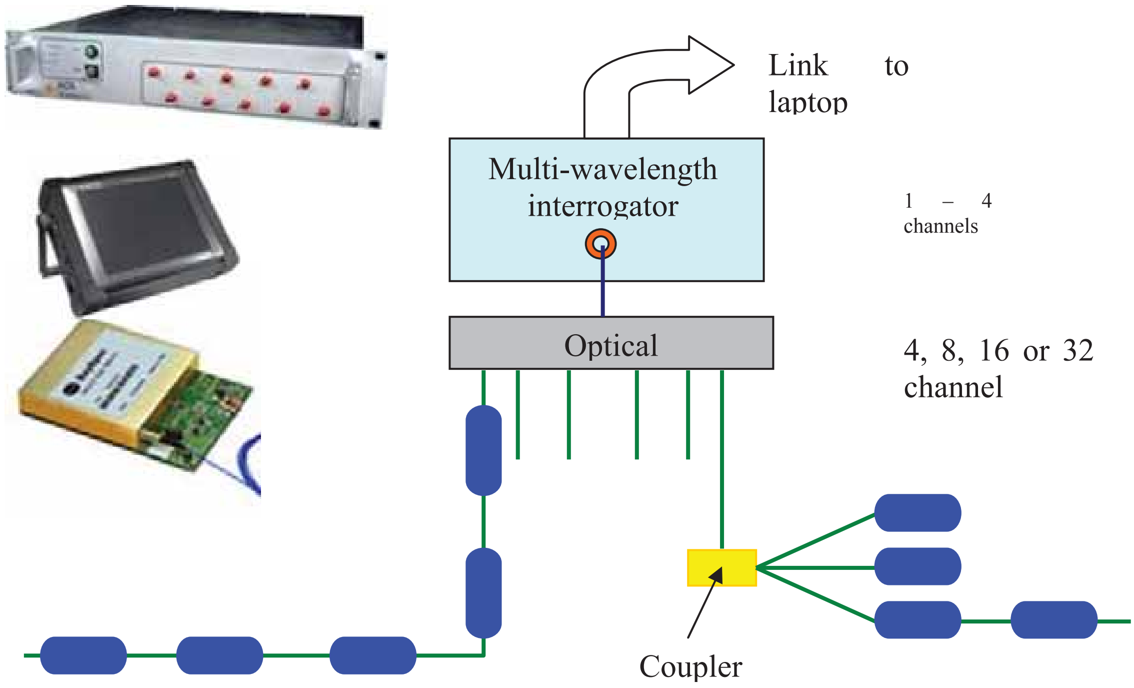

Figure 55: Scheme of the sensing network and pictures of various types of data acquisition unit for fibre Bragg gratings

Use in geological repositories

FP may find various applications in geological repositories, as a function of the coating and the related sensed parameter. More detailed description will be given in the paragraph dealing with chemical sensors. Concerning strain sensing, fibre Bragg grating could seem more attractive than FP because of its multiplexing capabilities.

- Temperature compensation
  Since 1°C and 10 με (defined as μm of mechanical variation of one meter of material) cause roughly the same influence on the Bragg wavelength, for the monitoring of underground repositories where high level wastes induce large temperature variations, it would be necessary to introduce specific systems to decorrelate these two phenomena. As such, each Bragg grating strain sensor is often associated with a second Bragg grating sensor dedicated to temperature measurement.

  The necessary distance between the two gratings could be reduced down to 1 or 2 centimeters (longitudinally), if the two grating are created on a single fibre strand. Standard configuration is to use two fibre coils with two gratings. If they are placed in the same measurement line, required distance is in the order of 15cm (linked with connectors or splices). The sensors can also be placed side by side if the two fibres are multiplexed with a "star" configuration. These various practical aspects are not to be neglected if the sensors are instrumenting high temperature gradients.

  The level of sensitivities and resolutions obtained are most attractive: 1 με and 0.1°C turn out to be typical values, in great accordance with required sensitivities in monitoring repositories.

Though this performance can be rated similar to that of LVDT sensors, one chief advantage herein is the great simplicity of implementation by virtue of both a significant reduction in cable requirements and automatic sensor addressing. On top of economic savings, such multiplexing capability could reinforce safety (instrumentation less invasive) as cabling would be considerably reduced down to a single cable, eventually two to ensure reliability.

- Sensitivity to radiation
  However, a specificity to look after is the sensitivity of Bragg gratings to radiation. Indeed, Bragg gratings are created into photosensitive optical fibres, usually highly doped with Ge. However, this dopant is also quite sensitive to gamma radiation which could provoke high propagation losses if used near radiation sources such as wastes. Recently, various technologies have emerged to solve this problem, such as long-period gratings (LPG) made in special radiation-hardened optical fibres, as described with greater detail in 3.1.2.6.

Long-based fibre-optic strain sensors

<u>Principle</u>
Quasi-distributed sensors are composed of large Fabry-Perot cavities (> 20cm) induced by several inline partial mirrors in the fibre. Such sensors perform intrinsically integrated measurement into the optical fibre. The main advantage of this technique compared to point-like measurement is to avoid any dead-zone, as shown in Figure 52.

The SOFO product created by Smartec/Roctest/Telemac company (see picture in Figure 56) has dominated over the past five years, chosen for installation on many engineering structures, notably on the Millau Viaduct. Its originality is to associate two FP cavities inside a unique sensor coating: two optical fibres are placed in a tube, the first being tensioned between two structural anchorages, while the second left free to dilate with temperature variations, which tend to be self-compensating. The length offset between these two optical fibres is reproduced in the read-out box via architecture similar to the principle depicted in 3.1.2.2. Such strain sensors are very sensitive, i.e. up to 2 με of resolution regardless of strain sensor length.

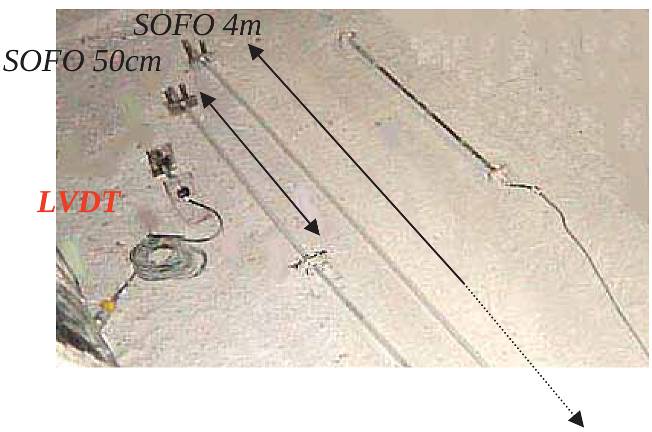

Figure 56: Picture of conventional sensors (LVDT) placed in parallel with 50-cm and 4-m SOFO strain sensors installed in the central arch of a concrete bridge [92]

Then research dealt with long-period strain sensors with external coatings that enable maintaining their flexibility and ensuring a continuous bond with the application medium even on curved surfaces (SMARTape product created by Smartec-Telemac-Roctest company) [93].

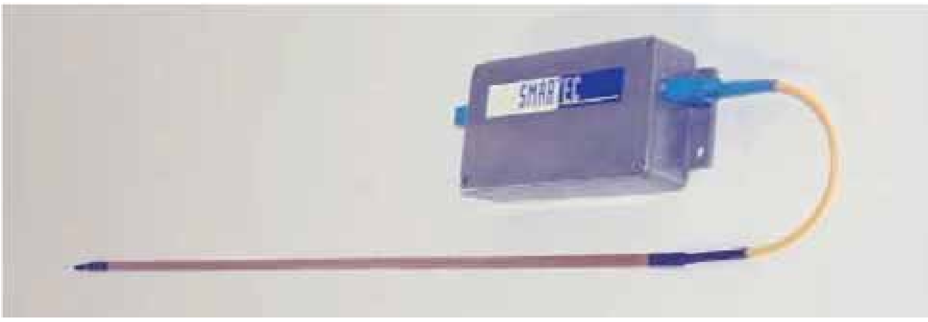

Figure 57: Picture SOFO strain sensors with curved shape

Sensor multiplexing could only be carried out in parallel, thereby removing one of the major advantages associated with fibre-optic sensors. Other companies have overcome this limitation through use of partial mirrors placed end-to-end along the optical fibre [94] [95]. Yet, the number of sensors lying on the same fibre is currently still restricted to around ten. Beyond a hundred meters of instrumented span, in seeking to lay out kilometer-long strain sensors, the use of distributed fibre optic sensors becomes mandatory.

Use in geological repository

Interferometric sensors (SOFO type from SmarTec) with different lengths have been installed in the HADES underground research laboratory. Short-length sensors (25 cm) have been embedded in concrete gallery lining segments, while longer sensors (5 and 10 m) have been installed in boreholes (for use as borehole extensometer) and in the PRACLAY Gallery itself (three 10 m-long sensors in series to monitor the overall expansion or contraction of the gallery). OFS were chosen here because of the inherent simplicity of the sensor compared to the common extensometer types (such as rod extensometers), which showed a poor performance in the Boom Clay environment – and where we could expect particular problems with a measurement head to be installed in the saturated and heated gallery. At the moment of writing (March 2011), assessment of the sensor performance is still limited as the gallery has not been saturated and heated yet. The installation of the OFS and operation at the gallery highlighted some peculiarities compared to traditional copper-wired sensors: connecting fibres needs special care regarding connectors (easily damaged during field works, splicing less convenient), while the read-out is rather laborious (portable PC in conjunction with the read-out), which should be minimized considering the long-term nature of the field set-up's. The sensors needed additional protection as the water pressure (up to 3 MPa) and temperature (95°C and higher inside the gallery) that we expect during the experimental phase exceed the sensor specifications. Care had to be taken that this protection does not influence the measurement performance of the sensor (e.g. a full steel casing of the sensor could affect the measurements due to the thermal expansion of the casing).

Distributed (continuous) fibre optic sensors

Principles: scattering phenomenon and localization processes

The term *distributed sensor* designates the case in which the optical fibre itself becomes a sensor. It is thus no longer necessary to implement anticipated sensor positions since measurements are being performed all along the optical fibre plugged up to the reading device (as well as within the extension cables!). In addition, the processing and manipulations required to configure Bragg gratings or mirrors delimiting FP cavities act to significantly weaken the optical fibre. On the other hand, for distributed OFS, the commercial optical fibre is placed directly inside its mechanical protective coating, which would suggest a more robust instrumentation.

Various techniques may be utilized to develop a continuously-distributed measurement system within an optical fibre as described in great detail in [96] [97]. It associates principles based on optical scattering, sensitive to strain and temperature variations as described below in Principles for temperature and strain sensing, with localization processes described below in Principles for localization.

- Principles for temperature and strain sensing
  As shown in Figure 58, the light backscattered by an optical fibre segment without any defects or abnormal characteristics is spectrally decomposed into three distinct peaks corresponding to three outstanding phenomena.

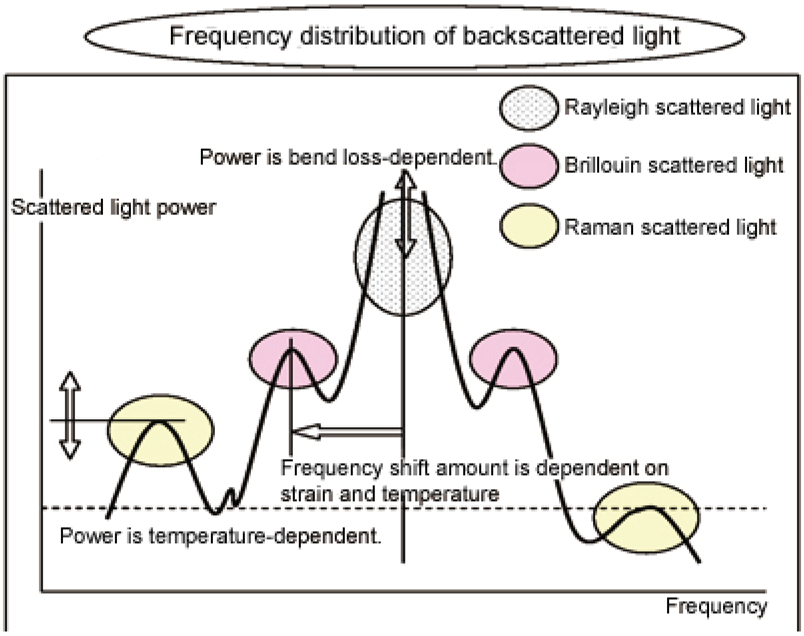

Figure 58: Spectrum of backscattered light inside an optical fibre

The first relates to Rayleigh scattering. The electromagnetic wave propagating in the fibre core interacts with the scattering centers, silica impurities and enhancing additives with dimensions well below the wavelength. By measuring intensity variations in the backscattered signal at the same wavelength as the injected wave, local optical fibre modifications may be detected: an abrupt return peak is interpreted as a mirror reflection (connector or damage on the fibre), and a sudden drop in intensity corresponds for example to shear loss. As pointed out in section 3.1.2.1, however, light intensity variations cannot be directly correlated with deformations of the medium where the optical fibre has been embedded.

The Raman effect is an interaction between light and the corresponding coupling matter between a photon and the thermal vibration of silica molecules. As such, this phenomenon is highly dependent on temperature. More precisely, the anti-Stokes intensity evolution (low frequency component) must be augmented with a reference measurement since optical fibre losses vary with time (increase with fibre aging, connector dirt or optical fibre curvatures etc.). A solution commercially implemented is to analyse the ratio between the Anti-Stokes and Stokes (high frequency component) absorption line intensities (I_{RAS} and I_{RS}).

This Brillouin frequency shift ν_B is linked to the *acoustic* mode phase velocity. As a consequence, its variations are known to be proportional to temperature and strain variations, parameters are noted C_T and C_ε. They are characteristics of the optical fibre type. At the operating wavelength (1550 nm), for standard G652singlemode fibre, C_T and C_ε are in the order of 1MHz/°C and 0.05 MHz/με [98].

- Principles for localization
  Localization can be implemented through three techniques, all based on reflectometry: OTDR (Optical Time Domain Reflectometry), OLCR (low coherence frequency domain reflectometry) and OFDR (coherent optical frequency domain reflectometry).

  Initially created to analyze losses inside optical telecommunication lines, OTDR [99] is categorized as an optical pulse-echo technique. The technique consists in injecting a laser pulse within an optical fibre and then measuring the backscattered intensity versus time: a period Δt corresponds to a pulse round-trip between the lead and a given point on the fibre located at $c/(2n \cdot \Delta t)$ from the lead. The temporal width of the pulse necessitates an OTDR spatial resolution; a 10-ns width corresponds to a resolution of 1 m. OTDR serves to carry out intensity variation measurements over distances in the tens of kilometers, with a spatial resolution at the meter scale.

  Other localization techniques are available; some for example based on frequency modulations, hence the acronym OFDR (Optical Frequency Domain Reflectometry). Detailed principle can be found in [100]. OFDR spatial resolution can reach 10 µm, although the corresponding measurement range (possible fibre length) diminishes considerably to around 100 meters. OLCR is used for measurements over a limited range (typically < 5 m), which limits it use to laboratory measurements.

  Whatever the technique, a major issue of distributed sensing is the uncertainty on the measurement locations along the fibre. As shown in [101], the difference between measurement locations estimated by different commercial devices could be up to 1% after only 85 m propagation into a unique sensing cable with two identical fibres, providing for an uncertainty of close to 1 m in data location. This is mainly due to the group index value (i.e. an index representative of light propagation speed in the fibre as the function of the wavelength) used during data processing. Moreover, the provided information is the curvilinear abscissa along an optical fibre coil, often partially embedded into structures to be monitored, often in the km range. As a result, location uncertainty is further conditioned by a sensor location map drawn during installation.

Commercially available instruments

Instruments combine a sensitive phenomenon with a localization process, as shown in Figure 59 for Brillouin strain sensing.

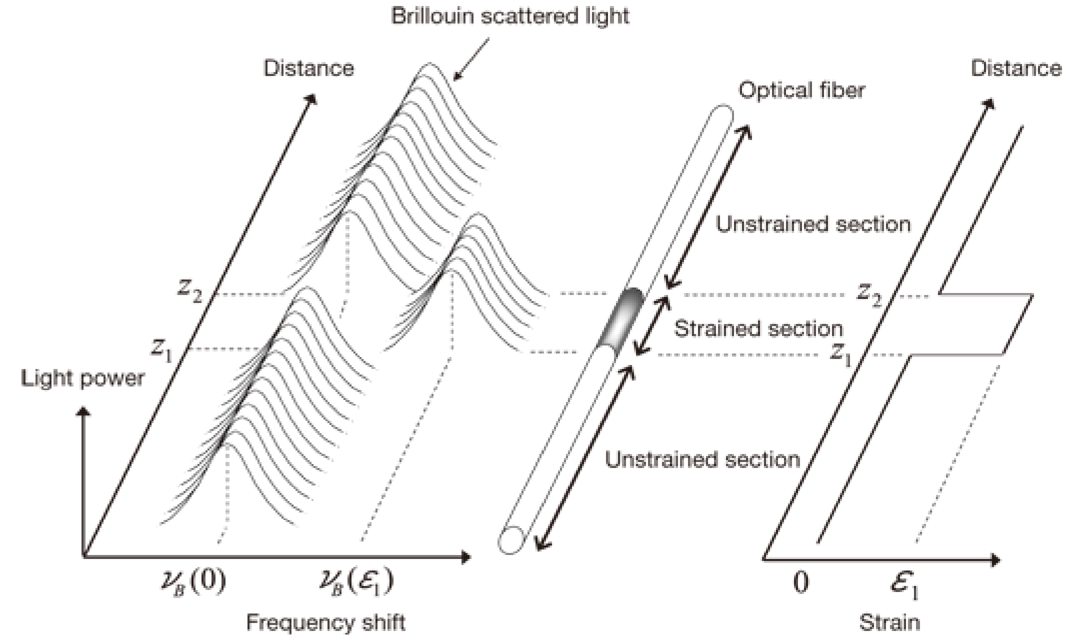

Figure 59: Example of distributed strain measurement in the case of Brillouin scattering

Several optoelectronic devices that conduct distributed temperature measurements using the Raman effect are in fact available on the market. Paired with multimode fibres, resolutions of Raman distributed temperature devices are on the order of 0.1°C for measurement locations distances of several kilometres. This temperature resolution degrades with increasing distance but can be maintained by increasing the device acquisition time. Measurements are always averaged over 1m spatial resolution; maximal distance range is 30 km. Raman device operating with singlemode fibres are available; Andra performed tests in 2008 with such instruments that revealed sensitivity on optical fibre curvatures is enhanced which may become too restrictive for outdoor civil engineering works [101].

As a case in point, a Raman system fire monitoring was installed on the Mont-Blanc Tunnel subsequently to the 1999 disaster. Another industrial use is performed by EDF company (Electricité De France) that has already implemented various field qualification of Raman scattering in multimode fibres. In the beginning of 2002 [104], although the optoelectronic instrument revealed some inabilities with field specificities, the sensing cable inserted inside a 2 km embankment (France) endured civil engineering construction works. Meanwhile optoelectronic instrument improved. Another embankment was instrumented with embedded sensors in 2006 [105]. On the basis of the positive results obtained in 2008 and 2009, EDF concludes to the qualification of this SHM technique and decides to improve the surveillance of 2 industrial sites per year by this monitoring technique. Now, the focus is given in the way measurements may be interpreted with greater precision and less false alarm using statistics [106]. Another perspective is to take advantage of similar systems with embedded optical fibres into dikes to perform underground hole detection as inspired by [101], making use of strain distributed measurements with Brillouin scattering.

B-OTDR instruments would thus perform either temperature or strain measurements. In 2002, the first commercial system based on the Brillouin effect was implemented. By 2007, the market had expanded to include at least five suppliers of Brillouin interrogation systems (Omnisens in Switzerland, Sensornet in England, OZOptics in Canada, Yokogawa and Neubrex in Japan). The performance derived is on the order of 1°C or 20 µ□ and 1 m of spatial resolution, over spans extending several tens of kilometers. The most widespread application is currently pipeline leak detection, based on temperature measurements [107]. Compared with Raman sensing, sensitivity is reduced by a factor 10. However, Brillouin sensing enables measurement along longer distance ranges, up to 80 km. Both differences are mainly related to the optical fibre type, respectively multimode and single mode for Raman and Brillouin sensing.

Two shortcomings are restricting the development of Brillouin technology. First, separating temperature from deformation influences requires the use of (i) cables incorporating two optical fibres, one of which being mechanically isolated or (ii) the use of Raman on top of Brillouin instrument in a parallel sensing line. Andra has conducted many tests on "loose tubes" which revealed it is not realistic to isolate an optical fibre over very long distances [101]. Second, the price of interrogation systems, in the neighborhood of 100 k€, limits technology profitability to cases where the number of local sensors replaced by a distributed measurement exceeds some one hundred units. Research on Brillouin sensing is extremely active, with respect to both the interrogation techniques for reaching centimeter-scale spatial resolutions [108][109][110][111] and the choice of new optical fibres to enable decorrelating thermal and mechanical influences [112] [113].

For strain sensing, another technology is developing rapidly. The American firm Luna Technologies has been marketing since spring 2006 an optoelectronic device that enables measuring optical fibre strain (at a constant temperature, or the opposite, that is to say temperature at a constant strain) over 150 m with a millimeter-sized spatial resolution and a level of precision equal to a few microstrains. This performance has been obtained by OFDR, in association with an advanced correlation method between the ongoing measurement and a reference state; the spectral lags of the Rayleigh backscattering peak can thus be analyzed [103].

Use in geological repository

For geological repositories, taken into consideration the vitality of this research area, major improvements can be expected within the coming decade. If design had to be fixed now, for Raman temperature sensing, sensing cables that pair one monomode fibre for strain sensing and one multimode fibre could be a reliable configuration. Strain sensing technology could be either Brillouin or OFDR, as a function of distance range and spatial resolution (Brillouin when distance range exceeds 2km and OBR for shorter distances to benefit from better spatial resolution). Andra has currently (2009-2012) 3 PhD students working on distributed sensing improvements. One deals with the choice on the sensing cable. The sensing cable transfer functions of the strain field from the host material to the optical fibre are characterized; material aging are taken into consideration; finally, in view of concrete crack detection, strain field homogeneity versus spatial resolution is studied [114]. The second PhD focuses on the influence of optical fibre dopants on Brillouin scattering (how to design the Brillouin spectrum) [115]. The third PhD studies the influence of gamma radiation on Brillouin temperature and strain sensing [116]: can Brillouin scattering be performed in harsh environment fibres? Are temperature and strain coefficients dependant on radiation? Moreover, Andra participates into various outdoor tests. After the installation of optical fibres in the Andra Technologic building [101], in 2011, distributed optical fibre sensors will be installed in Bure underground laboratory in structures similar to storage cells.

Andra also takes part in a European COST Action numbered TD1001, launched in 2010. Called OFSESA for "novel and reliable optical fibre sensor systems for future security and safety applications", where it focuses on reliability and metrology of such novel systems. A typical option when considering temperature measurement is the installation of medium-length fibres (up to a few 100's m) inside protective tubing, allowing replacement of the fibre.

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3.1.2.3 Chemical optical fibre sensors

Optical fibre sensors have been used to monitor physical parameters such as temperature and pressure (see previous section), but lately people have realized their potential in the area of chemical and biological sensing. This section presents techniques to modify the optical fibre for chemical sensing applications.

Use of optical fibres to sense chemical concentration has been reported in literature since 1946. Since this date, optical fibre sensors have found applications in chemical [106], [117] to [121], biochemical [122] to [125], biomedical and environmental [126] to [129] sensing. They typically make use of an additional coating, either placed along the optical fibre or on the fibre tip. The chemical to be sensed may interact with the sensitive element by changing the absorption, reflection, scattering properties, change in luminescence intensity, change in refractive index or a change in polarization behaviour, hence changing the reflected light properties.

Extrinsic fibre optic chemical sensors: Optode

The basic optode design consists of a source fibre and a receiver fibre connected to a third optical fibre by a special connector as shown in Figure 60. The tip of the third fibre is coated with a sensitive material. The fibre only acts as a light pipe transporting light to and from the sensing region.

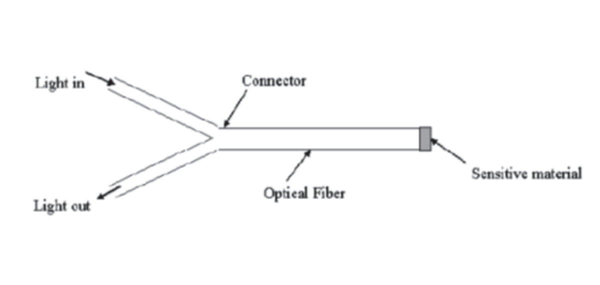

Figure 60: Principle of fibre optic optode for chemical sensing

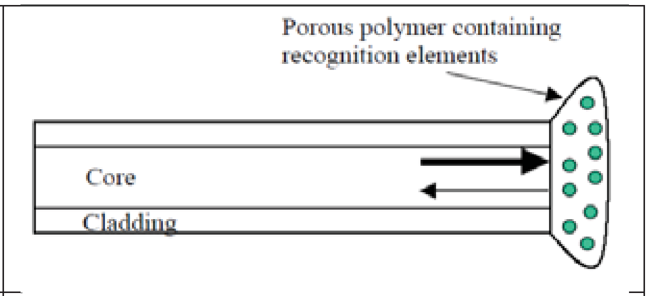

Figure 61: Optode configuration to enhance sensitivity

An example of an oxygen sensing micro-optode is shown in Figure 62, the measurement principle of oxygen is that of collisional quenching of luminescence by oxygen. The luminescent indicators used are either fluorescent dyes, like transition metal complexes [127] or phosphorescent dyes like platinum or palladium porphyrins [128]. The process of dynamic quenching of luminescence by oxygen changes the absolute emitted luminescence as well as the decay or life time of the luminophore. The optode design is also used in bio-sensing to recognize molecules immobilized at the distal tip of optical fibre [130]. The change in optical properties which are brought about by the binding of the analyte to the optode tip are transmitted through the fibre to the detector, these are generally fluorescent signals.

Figure 62: Portable oxygen micro-optode provided by ocean optics®

The main problem associated with this design is the size of the area of interaction between the chemical and the material. As described in *Optical fibres* (3.1.2.1), the fibre core is as small as 10 microns in diameter in the case of single mode fibre and 50-200 microns in the case of multi mode fibre, which directly affects the sensitivity achieved from this type of sensors. To circumvent this limited sensitivity issue, these biosensors utilize a porous polymer or a semi-permeable membrane or even porous beads which contain the recognition molecules as shown in Figure 61. This provides with an increased surface area available for reaction with the analyte, enhancing the sensitivity of the design.

With regard to long-term monitoring a good sensitivity is not enough. One problem still to be solved is the aging effects of the chemicals especially if enhanced by illumination. This results in a significant drift of the sensing system which can hardly be calibrated or compensated. Significant R&D seems necessary at that point.

Intrinsic fibre optic chemical sensors

There are four general sensor designs for intrinsic fibre optic chemical sensors:

- Fibre refractometer,
- Evanescent spectroscopic,
- Active coating,
- Active core.

Fibre refractometer

The fibre refractometer is shown in Figure 63. In this design the core of the optical fibre is exposed and the fibre is bent in a U shape. The presence of the analyte in the vicinity of the bend causes a change in the refractive index of the surrounding which changes the bend losses through the optical fibre causing a change in the transmission efficiency through the optical fibre.

The application of this design is mainly in liquid level sensing [129]. Small air bubbles in liquid can also be detected by this design [131]; as a consequence, this technique can also be applied to detect air leaks in pipe lines.

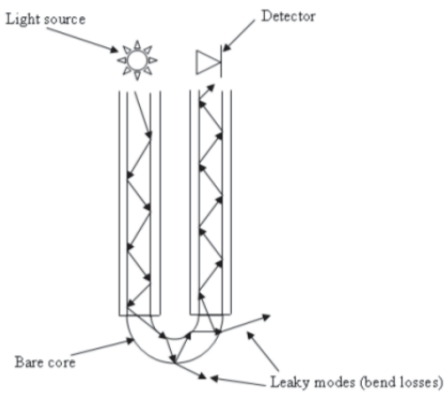

Figure 63: Schematic of optical fibre refractometer

Evanescence spectroscopic

The evanescent spectroscopic sensor design uses the evanescent field associated with the propagation of light in optical fibres. The evanescent fields can be used to transfer energy out of the core to absorbing species in the surrounding medium (*evanescent absorption*), to create fluorescence in the region outside the core (*evanescent excitation*) or to couple fluorescence from surrounding medium into the fibre core (*evanescent collection*).

The evanescent spectroscopic type design is shown in Figure 64. The change in optical transmission properties is caused by optical absorbance of the analyte. These sensors require the analyte to be optically active (should show intrinsic fluorescence) in the wavelength range of the light in the optical fibre.

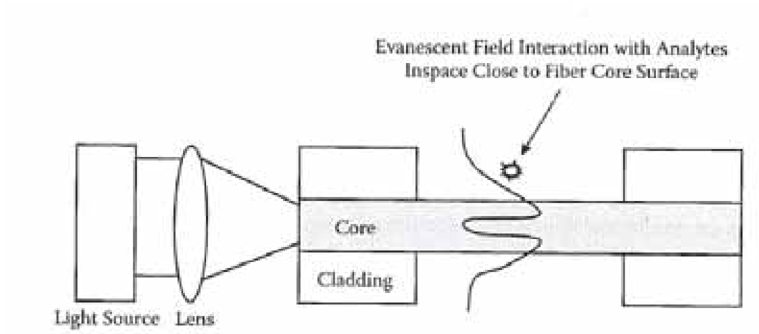

Figure 64: A schematic chemical sensor on fibre coupled evanescence waves

Recent research in this area has therefore been focused mainly on pushing the wavelength range of this technique into the mid-infrared or the "chemical fingerprint" region of the electromagnetic spectrum. This design has found applications in in-situ gas diagnostics [132].

Coating based

Coating based sensors are the largest class of intrinsic fibre optic chemical sensors. In this design a small section of the optical fibre passive cladding is replaced by an active coating [133]. The analyte reacts with the coating to change the optical properties of the coating.

A novel fibre optic hydrogen sensor which is constructed by depositing palladium over an exposed core region of a multimode fibre is reported [134]. The sensing mechanism is based on evanescent field interaction with the palladium coating. The transmission properties of palladium films are reported to change with hydrogen adsorption which leads to a change in the complex refractive index. Hydrogen diffusion into Pd leads to the formation of PdH which modifies the work function of Pd changing its electrical and optical properties. The reported sensor can detect hydrogen in the 0.2–0.6% range with corresponding response times of 30–20 s at room temperature. Sol-gel based microporous silica coatings which often serve as a matrix to the sensitive material have been extensively applied to optical fibre coating based sensors for chemical and bio chemical sensing.

SOMOS Project : comparison of 3 techniques

In the framework of the SOMOS European Community research project [172] three different types of hydrogen sensing OFS have been investigated by the Spanish research organisation CSIC. The first type was based on the optical fibre as an intrinsic sensor element. The spectral absorption of an optical fibre exposed to gas mixtures with H_2 concentrations of 2% and 4% has been studied in the spectral range [1150 nm ; 1700 nm]. It shows several absorption peaks related to hydrogen. The main absorption peaks are located around 1245 nm and 1390 nm, but the second is related to OH- ions and is not reversible. Another absorption peak at 1315 nm is not sensitive for low levels of H_2 thus is suitable to be used as reference to measure the relative changes in the peak at 1245 nm. The attenuation due to the uptake of H_2 in the fibre is reversible. The second type is based on Pd semitransparent film sensors. In this case a 18nm Pd thickness film is deposited on a SiO_2 substrate. Both the transmittance and the reflectance can be used as a sensing mechanism. The sensitivity of this sensor is independent of the wavelength in a wide spectral range (1200 to 1600 nm). The prototype allows determination of up to 1.5% (vol) of H_2, and it shows good reversibility at these levels. Higher levels might cause a phase change in the PdH system, resulting in different sensor behaviour and change in adherence of the Pd to the substrate.

A third type is based on Pd-coated fibre Bragg gratings (FBG). A Pd layer deposited over a fibre Bragg grating is the essential part of the design. When a Pd film absorbs H_2 it expands because Pd converts to PdH_X which has a larger volume. When a Pd coated FBG absorbs H_2, the mechanical expansion stretches the fibre which causes a change in the characteristic reflected wavelength of the FBG due to the induced (extra) strain in the fibre. In order to enhance the strain produced by the H_2 absorption, a small diameter FBG must be used (20–30μm). Although the working principle was verified, further development is needed to achieve improved sensitivity and robustness.

More precisely, for application in repositories, the long-term behaviour and influence of radiation are aspects that need to be addressed. An example is the oxidation of Pd that was observed – and that delayed the absorption of H_2.

Core based sensors

Core based optical fibre sensors require use of special fibres made from porous glass. The core is sensitized by adding chemically sensitive reagents on the surfaces of the pores. The response time of these sensors is very long so this technique finds applications where dynamics is less important than sensitivity. There is very limited literature available for this type of sensor since (i) very few research groups work in this area (ii) the fabrication of porous optical fibre can be a difficult task. Pioneering work has been conducted by Macedo [135] Shahariari [136] and Zhou [137]. A reversible porous glass pH sensor has been reported with response in the range pH 4.0-7.0, also a reversible ammonia sensor with sensitivities in the lower ppm has been reported. Recently a novel sol-gel process for making porous silica core fibre has been demonstrated [138]; this fibre was then applied for humidity sensing.

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3.1.2.4 Hygrometry optical fibre sensor

At this point, humidity optical fibre sensors pertain to laboratory developments. Various techniques are studied, with specific advantages and drawbacks. A review paper on the use of fibre optic sensor technologies for humidity sensing is presented by T.L Yeo et al. [139] which is relatively exhaustive. In a similar way to temperature and strain, humidity constitutes one of the most commonly required physical quantity.

The following tables (Table 4, Table 5, Table 6 and Table 7) show performances, detecting ranges and response times of available hygrometric optical fibre sensing depending on the general principle used. The maturity of such humidity sensor is mainly prototype near or at planned operational system.

Table 4: Direct spectroscopy

Reference	year	authors	Sensing method	Sensing material	Range (%Rh)	Response time
[140]	1988	Zhou et al.	Direct in-line absorption	Etched borosilicate optical fibre segment doped with CoCl2	20-50	< 5 min
[141]	1988	Posch and Wolfbeis	Fluorescence quenching	Perylene dyes	0-100	
[142]	1995	Raichur and Pederson	Fluorescence quenching	Aluminium/morin metal ion–organic complex doped PVP membrane	0-80	
[143]	1997	Brook et al	Absorption	Crystal violet doped Nafion film	40-82	
[144]	1998	Otsuki et al.	Direct in-line absorption (open air-gap configuration)	Rhodamine B doped HPC film	0-95	~ 2 min
[145]	2001	Glenn et al.	Fluorescence lifetime	Lithium-treated Nafion membrane	-	
[146]	2004	Tao et al.	Direct in-line absorption	Porous sol–gel fibre segment doped with CoCl2	2-10	~ 2 min
[147]	2006	Bedoya et al.	Fluorescence lifetime	Ruthenium-based complex doped PTFE membrane	4-100	< 1 min

Table 5: Evanescent wave

[148]	1985	Russell and Fletcher	Absorption measurement using straight and U-bent fibre	CoCl2 doped gelatine film	50-80	
[149]	1988	Ogawa et al.	Attenuation measurement using OTDR technique	Porous SiO2 optical fibre cladding	25-95	
[150]	1995	Kharaz and Jones	Absorption measurement using OTDR technique	CoCl2 doped gelatine film	20-80	1s
[151]	1998	Otsuki et al.	Absorption measurement using U-bent fibre	Rhodamine B doped HPC film	0-95	~ 2 min
[152]	2000	Kharaz et al.	Absorption measurement using U-bent fibre	CoCl2 doped HEC and gelatine films	H :30-96 G :40-80	5s
[153]	2000	Bariain et al.	Attenuation measurement using tapered fibre	Agarose gel	30-80	<1min
[154]	2001	Gupta and Ratnanjali	Absorption measurement using U-bent fibre	Phenol red doped PMMA film	20-80	

[155]	2002	Jindal et al.	Absorption measurement using straight and U-bent fibre	CoCl2 doped PVA film	S :>78 U :3-90	
[156]	2003	Muto et al.	Attenuation measurement using PMMA plastic optical fibre	HEC/PVDF film	20-80	<5s
[157]	2003	Arregui et al.	Attenuation measurement	Hydrogels-Agarose gel, poly-HEMA, poly-*N*-VP, poly-acryamide	Agarose 10-100	~90s
[158]	2004	Gaston et al.	Attenuation measurement using side-polished fibre	PVA film		1 min
[159]	2004	Alvarez-Herrero et al.	Wavelength resonance shift using side-polished fibre	TiO2 overlay		
[160]	2004	Xu et al.	Attenuation measurement	Porous sol–gel cladding		< 1min
[161]	2006	Corres et al.	Attenuation measurement using tapered fibre	PDDA/Poly R-478 nanostructured sensing overlay using ISAM technique		

Table 6: In fibre grating

[162]	2002	Kronenberg et al.	Strain-induced Bragg wavelength measurement	Polyimide	10-90	
[163]	2002	Luo et al	LPG resonant band wavelength measurement	CMC	0-95	
[164]	2005	Tan et al.	LPG resonant band intensity measurement	Gelatine	90-99	
[165]	2005	Konstantaki et al.	LPG resonant band intensity and wavelength measurement	CoCl2 doped PEO film	I : 70-80 W :40-80	<1s

Table 7: interferometric

[167]	1989	Mitschke	Intensity measurement using Fabry–Perot configuration	SiO2–TiO2–SiO2 cavity	0-80	1min
[168]	1999	Arregui et al	Intensity measurement using Fabry–Perot configuration	SiO2–[Au:PDDA+ /PSS-]-air cavity using ISAM technique	11-100	1.5s
[169]	1999	Kronenberg et al.	Tandem Michelson interferometer configuration	PUU-PEO/PPO Hydrogel		
[170]	2001	Yu et al.	Intensity measurement using Fabry–Perot configuration	SiO2–[PDDA+ /PS-119]-air cavity using ISAM technique	0-97	3s
[166]	2007	Venugopalan et al.	LPG resonant band intensity measurement	PVA	33-97	

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3.1.2.5 Pressure

To our knowledge, there is no direct phenomenon sensitive to pressure. Thus commercial implementations of pressure optical fibre sensors are obtained thanks to a global chain, including a special transduction mechanism as previously mentioned in *Extrinsic versus intrinsic sensors* (3.1.2.1). Total pressure and porewater pressure sensors are important to monitor fluid pressure in the backfill (e.g. in crushed rock salt for the current German concept) and for monitoring rock stresses to evaluate the dilatancy behaviour of the host rock.

Pressure sensor based on Fibre Bragg Gratings

Figure 65 shows the basics of one transduction mechanism: the relative displacement between the fixation points is transmitted to the FBG through capillaries in which the fibre is glued. Using this mechanism, pressure (Figure 65-b) is converted into a strain applied to the FBG.

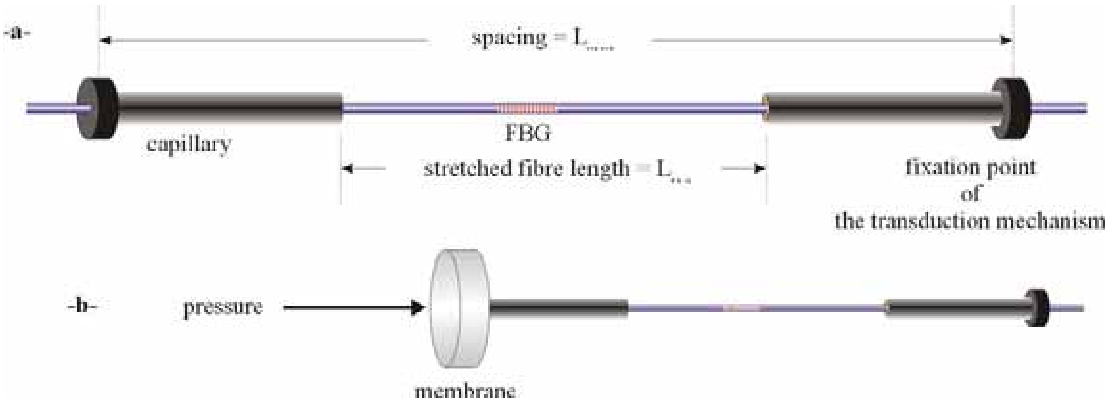


Figure 65: Transduction mechanism used in the pressure sensor (source: FOS&S)

A FBG is pre-stretched between the centre of a circular membrane and the body of the sensor. Pressure to be measured is applied onto the membrane and bends it slightly resulting in a displacement of its centre. The FBG is thus released by increasing pressure while it is stretched by decreasing pressure. The FBG spectral shift $\Delta\lambda_{FBG}$ is proportional to the pressure difference $P - P_{atm}$ according to Equation I (b_{FBG}: FBG strain sensitivity, $L_{0\,FBG}$: FBG length at rest, th_{memb}: membrane thickness, Y_{memb}: membrane Young' modulus, σ_{memb}: membrane Poisson ratio).

Equation 3.1.2.5-1

$$\Delta\lambda_{FBG} = b_{FBG} \cdot \Delta\varepsilon_{FBG} = b_{FBG} \cdot \frac{\Delta d_{memb}(th_{memb};Y_{memb};\sigma_{memb};(P-P_{atm}))}{L_{0\,FBG}} = S_P(b_{FBG};L_{0\,FBG};th_{memb};Y_{memb};\sigma_{memb}) \cdot (P-P_{atm})$$

Fibre optic membrane pore water pressure sensor

Figure 66 shows a pore water pressure optical fibre sensor. Two Bragg Gratings are placed in the stainless steel housing for temperature compensation. One grating (FBG-1) is attached to the membrane (as indicated in Figure 66b) measuring the strain on the membrane from which the pressure can be calculated (Equation 3.1.2.5-1). This grating is however also influenced by temperature. For distinguishing the strain and temperature effect, a second grating (FBG-2) is placed in the same housing (at the same temperature as FBG-1) which is only reacting on temperature changes. This allows complete temperature compensation.

A porous stone is used to allow easy penetration of the soil water that is acting directly at the transduction membrane.

A commercially-available sensor from FOS&S company is illustrated in Figure 66. It has a typical length of about 270 mm with a diameter of about 27 mm. The cable length can range between 1m to 1km.


Figure 66: Pore water pressure sensor in different layouts

Fibre optic total pressure sensor
Similarly, almost any kind of sensors that are traditionally based on vibrating wire extensometers (VWE) can be transformed into optical fibre sensors by replacing the vibrating wire sensors VWS by a FBG, for instance. Any other kind of OFS could also be adapted.

An example is the pressure pad illustrated in Figure 67. The flat cell is filled with oil, which acts directly on the fibre optic sensor at the end of the pad.

Figure 67: Total pressure cell made of optical fibre sensors

Various ranges and sensitivities are available. They are highly dependent on the performance of the fibre Bragg grating interrogation unit, which strongly varies with the price of the unit.
Typical specifications are given as examples on Table 8.

Table 8: Typical specifications of pore water pressure sensors and total pressure sensors

	Type	Range	Resolution	Accuracy	Hysteresis
pore water pressure sensor	WP-FOSS 5	5 bar	0.01 bar	0.1 bar	< 1%
	WP-FOSS 10	10 bar	0.01 bar	0.1 bar	< 1%
	WP-FOSS 50	50 bar	0.075 bar	0.75 bar	< 0.5%
total pressure sensors	M-TP-FOS10	10 bar	0.01 bar	0.1 bar	< 1% F.S.
	M-TP-FOS150	150 bar	0.075 bar	0.75 bar	< 0.5% F.S.
	M-TP-FOS400	400 bar	0.075 bar	0.75 bar	< 0.5% F.S.

The graph below (Figure 68) shows an example of a typical calibration graph. The wavelength of the fibre Bragg grating is measured at a constant temperature as a function of pressure.

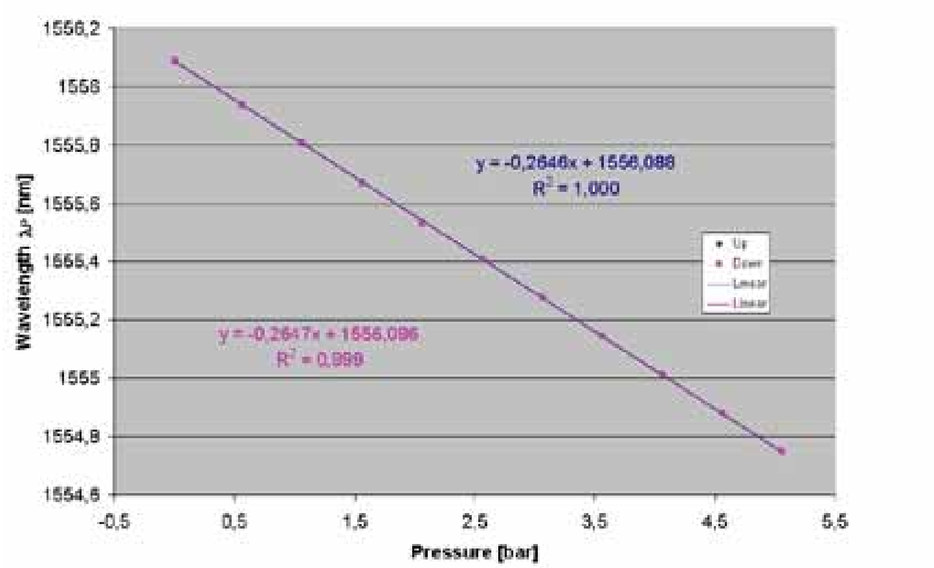


Figure 68: Calibration curve of a pore water pressure sensor at constant temperature

3.1.2.6 Radiation influence on OFS and optical fibre dosimeters

Recent developments on radiation resistant fibres resulted in optical fibres that endure quite high radiations losses: they are placed in CERN in Switzerland, MEGAJOULE LASER in France; ruggedized fibres also fly in satellites.

Definitions

The absorbed dose, noted D, defined by the amount of energy deposited in a unit mass in human tissue or other media. The original unit is the rad [100 erg/g]; it is now being widely replaced by the SI unit, the gray (Gy) [1 J/kg], where 1 gray = 100 rad

Dose rate - the quantity of radiation absorbed per unit time

Radiation influence on propagation losses in optical fibres

Gamma, UV and X radiations induce defects inside the silica material, which result into the increase of optical fibre propagation losses named RIA (radiation induced attenuation) or RIE (radiation induced emission) [171].

In the SOMOS research project [172], radiation monitoring based on radiation induced optical attenuation in optical fibres has been investigated. Two ways were considered: integrated, by measuring the total attenuation along the fibre sensing path, and distributed by employing

OTDR. Special doped fibres were chosen: in addition the P-doped fibres (that had shown good results in past studies), Er and Al-doped fibres were considered. The fibres show a first order (or even linear) increase of the radiation induced optical attenuation around 1300 nm to 1500 nm when placed in a radiation field. The temperature dependency of the response is negligible in the envisaged operating range (20 to 90 °C), while the dose-rate dependence was demonstrated to be low in a region between 1 and 100 Gy/h. The OTDR results were disappointing – the specifications claimed by the OTDR supplier were not met during the tests.

Since SOMOS project, researches have been intensive. It is now demonstrated that RIA depends on (i) the dose rate (see Figure 69), (ii) the total dose (see Figure 69), the working wavelength and the composition of the optical fibre (Figure 70).

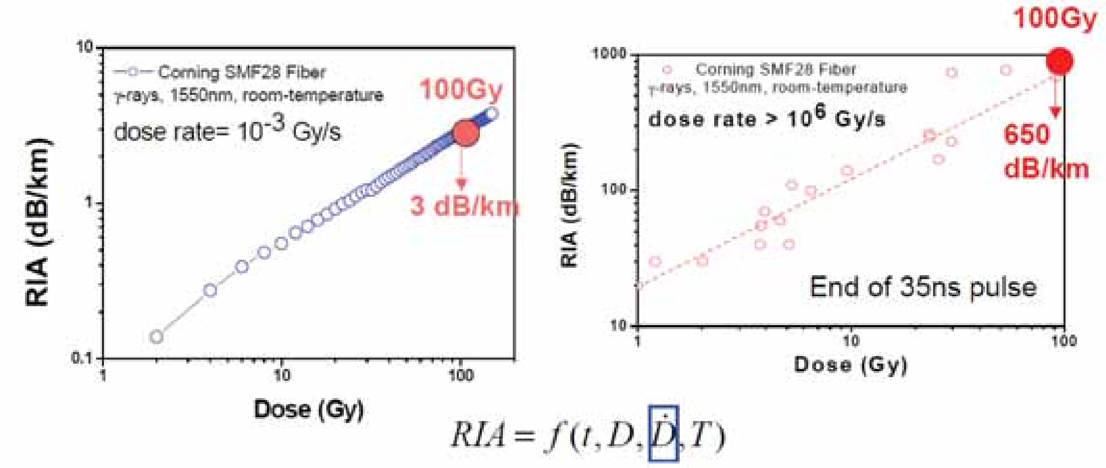


Figure 69: RIA at 1550nm as a function of □□dose for the most standard singlemode fibre (left), and blenching effects when radiation stops (right).

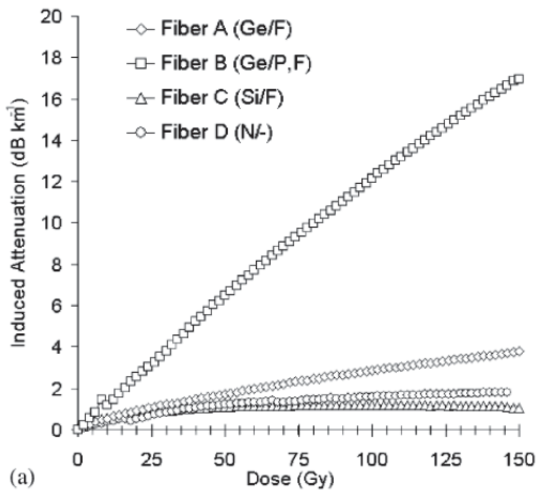


Figure 70: RIA at 1550nm for various silica fibre types as a function of □□□□dose [173]

The dopants types and concentrations have a major influence on the sensitivity of optical fibres to radiations [171], [174] [175]. Phosphor dopants must be avoided as illustrated in Figure 71. Up to now, the best silica fibres for radiation environment have optical core made of pure silica and guiding managed with fluorine in the silica coating [174] they are used to transmit the signal through areas of high levels of radiation [176]. The users should also consider the post-irradiation fading [177]. Post-irradiation fading is due to the repair of the physical damage caused to the material during irradiation. Post irradiation stability can be achieved through a range of treatment after irradiation, e.g. heat [178].

Finally, recovery can be observed when radiations stops as illustrated in Figure 71. It could also be linked with optical power.

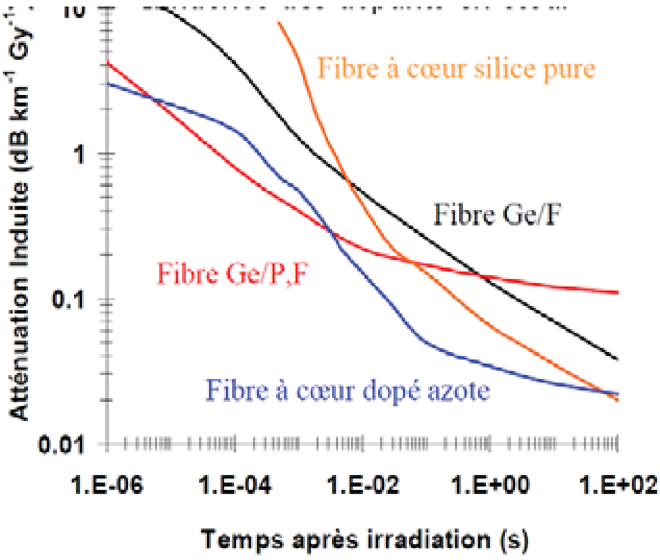


Figure 71: RIA for various irradiated silica fibre showing recovery when radiation stops [179]

Radiation influence on optical fibre sensors

Radiation influence on Bragg gratings

Photosensitive fibres chosen to create a Bragg grating are also sensitive to gamma radiations! Indeed, to obtain a permanent refractive index change, highly Ge doped fibres are selected, and are placed under hydrogen atmospheres to enhance their sensitivity. The thermal curing imposed after the UV insolation may not be sufficient to limit the radiation influence on the Ge doped fibres. Thus it can be stated that standard Bragg gratings are intrinsically highly sensitive to gamma radiations.

Radiation resistant FBGs for use in temperature and strain measurement applications in nuclear environments have been developed [180], [181], [182], [183] and [184].

Other technologies take advantage of Bragg interferences, but manage a high radiation tolerance by using radiation-hardened fibres with Bragg gratings inserted in the primary coating rather than in the core region. Refractive index difference between the different “slides” of the grating is much reduced. Yet the pitch can be significantly augmented, which generates a “long period fibre Bragg grating” (LPFBG). As illustrated in Figure 73, transmitted spectrum clearly shows a pick-dependency, which shifts under temperature and strain, like a standard Bragg grating.

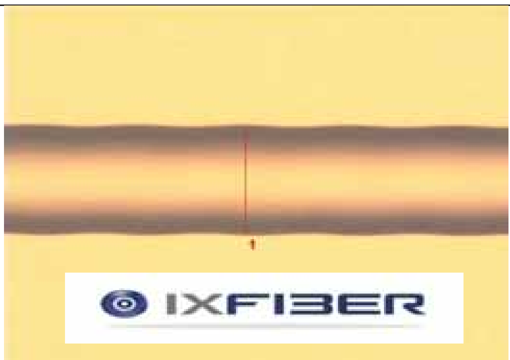


Figure 72: Picture of a Long period Bragg gratings commercialized by iXFiber company, obtained by varying the size of the primary coating which modifies the effective refractive index

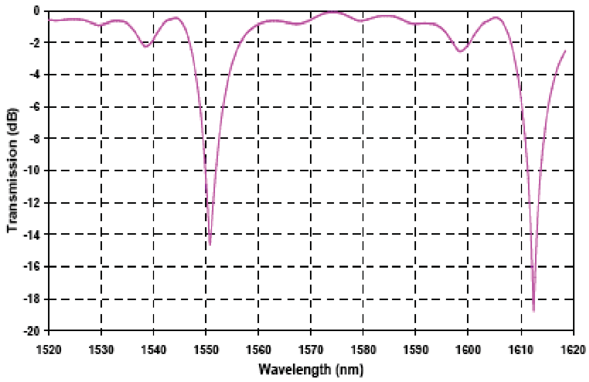


Figure 73: Optical spectrum transmitted through a LPFBG realized by geometrical modification of the primary coating of an optical fibre

Radiation influence on distributed sensors

Regarding Raman scattering, tests showed that current systems are able to cope with ionising radiation beyond 300 kGy [185].

Distributed temperature measurements have also been performed with an OBR Instrument that measures spectral shift of the Rayleigh scattered light (see 3.1.2.2) [186]. As illustrated in Figure 74, primary thermal response depends on the fibre coating and/or dopant level.

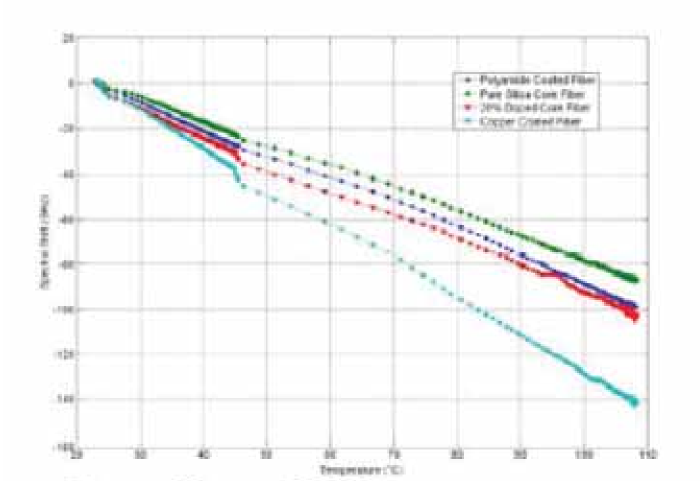
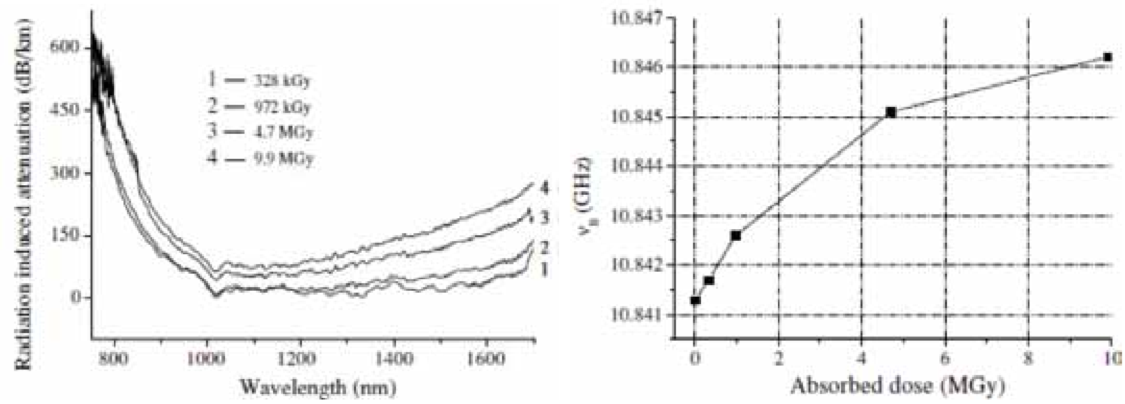


Figure 74: Spectral shift versus temperature [186].

Brillouin scattering has been investigated for use as distributed sensors within the nuclear industry and these sensors have been shown to be radiation tolerant up to 100 kGy. However, at high gamma doses, radiation-induced Brillouin shifts are observed [185] [187].



(a) (b)

Figure 75. (a) RIA under □□radiations (b) Corresponding variation of Brillouin frequency shift in the same fibre

Remaining questions are whether fluorine fibres paired with Brillouin device would results less sensitive and if the two coefficients that related frequency shift with temperature and strain are dependent. In the framework of Xavier Pheron PhD work, Andra and Laboratoire Hubert Curien and CEA have reproduced the result of Dario Alasia [185] using UV facilities (high gamma dose testing requires major investment in terms of equipment and costs): UV radiation may induce a non-neglectible Brillouin frequency shift change due to a compaction phenomenon depending on optical fibres. The photosensitive fibre shows a permanent change in the Brillouin frequency shift of 20MHz whereas SMF28™ properties remain quite stable [187].

Radiation optical fibre sensors

Already in [188][189], it is pointed out that the interaction of ionizing radiation with optical fibres leads to a variety of physical processes that principally can be used for radiation detection and measurement of the radiation dose rate or dose, i.e., for radiation dosimetry.

<u>Bragg gratings as radiation sensors</u>

The use of FBGs as high-dose radiation sensors was first presented in 2005 [190]. The work is based on the Kramer-Kronig dispersion relations, which can be used to show that an increase of attenuation has to be accompanied by a change of refractive index. The FBGs were written in a hydrogen doped Ge-doped fibre for wavelengths of 650, 820, 1,285 and 1,516 nm. The radiation induced refractive index change was calculated from the Bragg wavelength shift. A wavelength shift from 850 to 1,216 nm was demonstrated, as shown in Figure 76, and demonstrated to be independent of dose rate for radiation doses greater than 2 kGy. Although small changes in temperature are accounted for within the sensor system, the sensor requires a highly stable set-up, with stress-free attachment of the FBG along with a constant, steady temperature.

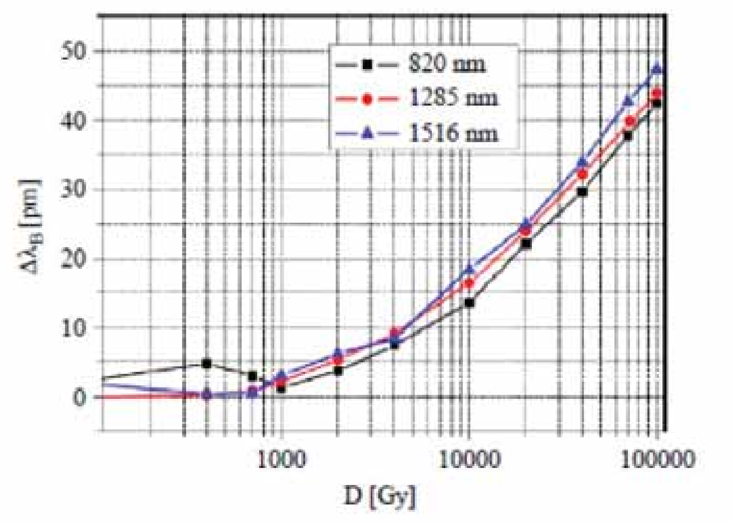


Figure 76: Shift of the Bragg wavelength during gamma irradiation

European Research Projects in the area of radiation optical fibre sensors

i-PROTECT (Intelligent Personal Protective Equipment system for personnel in high-risk and complex environments) is a FP7 project. It aims at developing highly advanced and intelligent personal protective equipment system that will ensure active protection and information support for personnel operating in high risk and complex environments in fire fighting, chemical and mining rescue operations. The core of the project is the integration of advanced materials and fibre optic sensors solutions aimed at real-time monitoring of risk factors (temperature, gas, oxygen level, etc.), users' health status (body temperature, heart rate) and changes of important protection features (e.g. end-of-service-life, air pressure in compressed units, etc.).

POFGaRD (Plastic Optical Fibre Gamma Radiation Dosimeter), funded by the European Commission under the 7th Framework Programme through the 'Marie Curie Reintegration' action of the 'Peoples' Programme (PERG04-2008- 239207), is concerned with developing a low cost radiation dosimetry system, based on commercially available plastic optical fibres, for monitoring ionizing radiation doses for biomedical applications

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3.1.2.7 Conclusion

Over the last twenty years, reliability issues had been detrimental to the market penetration of OFS. These difficulties have since been resolved by means of restriction to basically the interferometric family of techniques. Thanks to encouraging results obtained over the past few years, OFS are now being progressively implemented in structural health monitoring.

For underground repositories, optical fibre sensors’ sensor multiplexing ability is very attractive. Distributed technologies, i.e. continuous measurements along the optical fibre without requiring a preliminary definition of the exact measurement site, generates extremely promising prospects in the field of instrumentation. Strain and temperature distributed measurements are now commercially available. For repository monitoring, they would probably need a special protection for successful implementation: to endure water pressure and radiation under decades.

Chemical, hygrometry and radiation sensing optical fibre sensors still pertain to research. Application in geological repositories would thus require complete qualification procedure.

Context of application within Repository Monitoring

Controlling the state of a structure's health, more commonly designated by the acronym SHM (Structural Health Monitoring), requires a large number of sensors. The use of optical fiber sensors providing distributed measurements through the sensors’ multiplexing ability is very advantageous for monitoring of underground repositories. Distributed technologies, i.e. continuous measurements along the optical fiber without requiring a preliminary definition of the exact measurement site, generates extremely promising prospects in the field of instrumentation. Some 20 years of developments have been necessary to overcome the initial disappointments and fully utilize the specificities of these sensors [191], whose application has now reached the maturity required to be included with the state of the art of useful technologies. Instruments providing strain and temperature distributed measurements are now commercially available. They rely on scattering phenomena into silica cores of fibers, combined with localization processes (such as pulse-echo).

Among its possible applications, such distributed measurements may contribute to obtaining three-dimensional knowledge of the condition of the structure: by combining the information gained from other sensors in all monitored sections with measurements provided by the distributed optical fiber placed longitudinally along the structure, as shown in Figure 77. Within an instrumented section, several units are installed to detect possible asymmetries in terms of changes thermal, hydraulic, mechanical, and constitute a redundancy when the behavior is symmetrical.

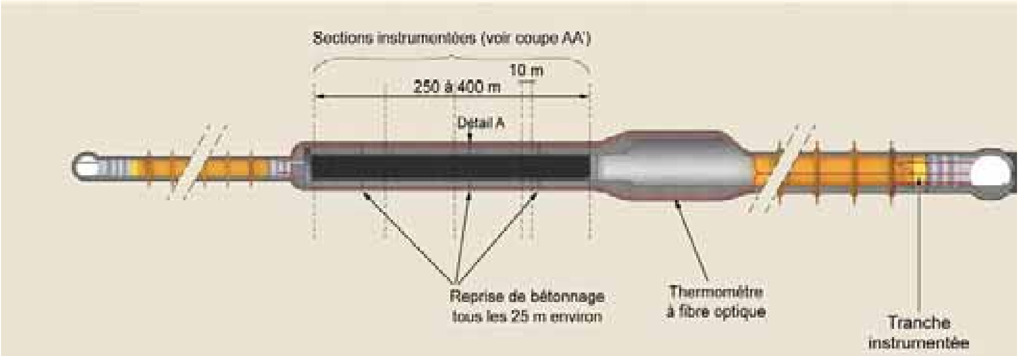

Figure 77: Optical fiber sensor repartition inside the concrete ILW cell

However, an optical fiber is too fragile to be used directly. The coating must also ensure an optimal transfer of temperature and strain fields from the host material to the optical fiber. Sensing cables are designed with different materials and shapes, either to be embedded in soil, metallic or concrete structures, or attached to their surfaces. Up to now, these cables have not been exhaustively tested. 1-1 scale laboratory experiments were carried out by Andra and its partners using various sensing cables and optoelectronic instruments, with controlled solicitations. Concrete specimens [192], a soil structure and a metallic structure were instrumented. Strain measurements performed with distributed sensing systems are found comparable to values obtained with conventional sensors used in civil engineering, namely vibrating wire sensor.

For certain specific repository monitoring applications near Waste Disposal Packages, OFS, like other sensor technologies, must resist and durably survive high gamma radiations. Andra tested various types of optical fibers and the influence of the dopants on the sensing performances. We started investigating the physics at the origin of the increase of propagation losses [193].

There are several multiplexing technologies for the fiber optic sensors. Quasi-distributed optical sensor system is realized by the interrogation of a series of point sensors along a single optical fiber. Compared with the fully-distributed sensors, the quasi-distributed sensor has much higher spatial resolution since an individual point sensor can be made very small, typically less than 1cm and as small as few tens of micron is achievable. Another advantage of the quasi-distributed sensor is it can generate much stronger optical signal and provides a much higher signal to noise ratio, therefore, yields higher measurement accuracy and resolution than fully distributed sensor. Two types of point sensors, the fiber Bragg grating sensor and fiber Fabry-Perot interferometer sensor, have been well investigated for quasi-distributed optical fiber sensing applications.There are many types of fiber optic chemical sensors which can measure concentration of neutral or charged species. Some of them will be used in order to measure gas or pH in the repository monitoring applications as soon as they fulfil the Andra qualification process [194].

References of use in previous experiences.
France's high-speed TGV rail network have been instrumented with optical fiber sensors: geotextiles are now able to detect, over the long term, the eventual appearance of cavities beneath the most recent TGV tracks; and fiber Bragg grating sensor have been embedded in test track made of concrete (without ballast) in the vicinity of Meaux (Paris Region) for the purpose of carrying out static and dynamic measurements (1 kHz).

Multiple instrumentations have shown the ability for distributed temperature measurements. For example, distributed temperature sensing thanks to Raman scattering into optical fibers was studied by EDF since beginning 2000's to detect leakages in dikes. The qualification methodology based on (i) laboratory and (ii) mock-up evaluation under controlled conditions and (iii) on complementary on-field tests was positively conducted. The metrological behavior of optoelectronic Raman devices of the market were evaluated. The sensitivity of the SHM technique was determined thanks to a full scale basin. Two industrial installations were realized in real conditions.

On the basis of the positive results obtained during the last years, EDF concludes to the qualification of this SHM technique and decides to improve the surveillance of 2 industrial sites per year by this monitoring technique. Overall results demonstrated efficiency of this whole leakage detection system based on Raman optical fiber sensing. Ongoing developments focus on quantification of leakages.

Another perspective is to take advantage of similar systems with embedded optical fibers into dikes to perform underground hole detection, as recently reported [195]. As a matter of fact, internal erosion has two main consequences: water leakage and soil deformation. For this perspective, strain distributed measurements are needed.

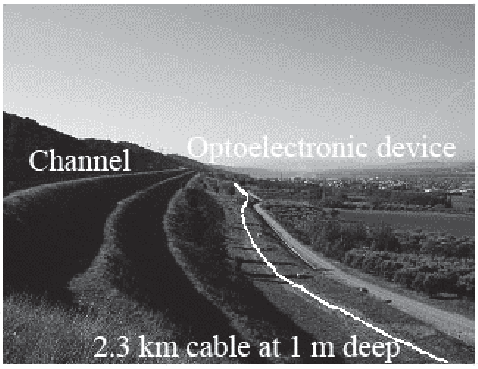

Figure 78: On field installation in the South East of France

The choice of a suitable sensor, in this case of the fiber and its coating, has important consequences on the quality of monitoring. A first field experiment was conducted at the underground research laboratory in Bure (Meuse / Haute Marne) of ANDRA, designed primarily to answer the following question: Is it possible to measure a temperature gradient on an industrial site, using single-mode optical fiber available in a standard, tight structure telecom cable, dedicated to data transmission, and this, with the Brillouin optical technology?

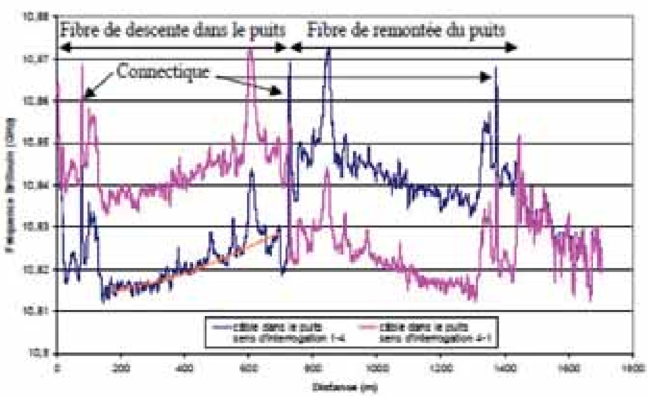

Figure 79: measurement obtained by the optical fiber installed in the shaft for data transmission

As illustrated in Figure 80, Andra's Technological Space construction was another opportunity to compare the laboratory performances of optical fiber measuring chains (sensors and optoelectronics) with field conditions. It is a 4700m² industrial building hosting exhibits of various prototypes equipments such as containers, large machines for radioactive waste handling (for instance a waste disposal container pushing robot), with the purpose of communicating with the general public and enhancing their understanding of geological repositories for radioactive wastes. As illustrated in Figure 81 several optical fiber sensing cables were installed at the core of the building concrete slab during summer 2008 construction. Five commercially-available sensors meant for distributed strain sensing had been selected after prior mechanical and thermal laboratory tests. Only two appeared promising for strain distributed sensing.

Figure 80: Picture of concrete slab pouring when concrete embeds reference sensors

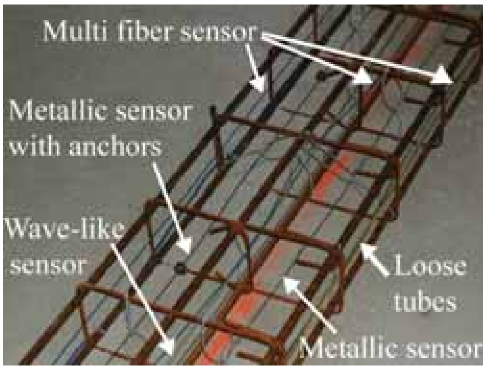

Figure 81: Optical fiber sensing cables fixed on reinforcing bar frame embedded into a concrete slab.

Brillouin-OTDR measurements were performed few months after pouring. Seasonal thermal variations are the main detected phenomenon. Few measurement points do not follow the global sensing chain behavior, but the 1 m spatial resolution and the 20 µm/m repeatability limit accurate interpretation. New optoelectronic Brillouin units with improved spatial resolution have not been tested yet. The distributed strain sensing experiment described in this subsection deals with relative Rayleigh measurements performed by the OBR instrument.

Figure 82: Picture of containers movements on the instrumented concrete slab.

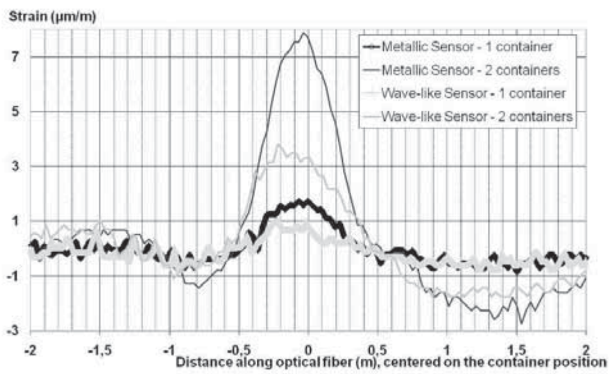

Figure 83: Distributed strain measurement performed by relative Rayleigh-OFDR measurements along two different strain sensing optical fiber cables

Limitations
Difficulty of all optical sensors is interference from multiple effects. A sensor intended to measure strain or pressure may be very temperature-sensitive. Intense R&D over the last five years to provide means for distinguishing between various effects has been conducted for optical sensors. Considerable progress has been made.

These installations enabled testing and validating several aspects of an on-field implementation.

Importance of the cable
The cable has to be robust in order to endure real civil engineering works conditions: handling, soil compaction... Moreover, it must resist to chemical aggressive environment (water and salinity). Inside dikes, rodents happened to destroy a cable, which can be solved by metallic protections. As a consequence, it is recommended to choose hybrid telecommunication cables meant for soil embedment. Moreover, its rigidity limits bending radius to approximately 0.5 m. For instance, Leoni supplies the cable described above.

Localization of the optoelectronics devices
Attention must be paid to selection of complementary materials. For both cases, the Raman devices were located within hydraulic power plants. The electromagnetic interferences generated by transformers and ambient temperature variations ruined measurements: approximately 50% time for the first two years of acquisition. Optoelectronic devices had to be included inside shielded and temperature regulated cabinets, with Uninterruptible Power Supply.. At the other extremity, at the end of the cable, the fiber was placed inside a closure within a cable connection pit for ulterior extension of the installation.

Remote control
As instrumented structures are distant from end-users; remote controlled solutions were implemented to provide rapidity in data processing and related warnings.

Exact localization of the event
While dealing with distributed data, a major difficulty is accurate event localization. Indeed, optoelectronic devices provide measurements in curvilinear abscissa along the sensing cable, which is far from the Euclidian distance at the surface of the dike. In practice, the sensing cable crosses a cable connection pit every 1km. Such access points enable creating artificial events by cooling or heating the cable, thus producing a clearly recognizable signal to which a known position on the structure can be attributed.

Similarly with longitudinal localization difficulty, transversal positioning is required. When an event is detected by this SHM technique, the soil needs to be dug to verify whether it is due to a leakage. To facilitate detection of cable position, in order to minimize digging works, commercially-available RFID devices were buried with the cable. This significantly enhances practical use of the technique.

Following prescription proposed in [196] as the fiber line was composed of different sensor types, all assigned to a specific Brillouin frequency shift, localisation was already ensured every 10m. Moreover, inspired by dike instrumentation know-how, the instrumentation map was drawn with a heating device enabling various controls prior to concrete pouring.

Reference for optical fiber
To perform valuable measurements, Raman systems require reference measurements, as clearly learnt from experience. To do so, Pt100 are included in the cabinet to enable easy and periodic device calibration. What is more, the 4 fibers are spliced by pair at the far extremity of the cable

in order to create an optical loop. As a result, the Pt100 is artificially compared to Raman measurements at two locations, one extremely closed and the second very far from the device. It also avoids maintaining reference sensors on-field.

Connection and splice
Sensor connections are of major importance. They necessitate extreme care during any handling which slower the instrumentation process. The optical fiber line was 250 m long interrupted by 18 FC/APC connectors and two splices. Unexpectedly, few fiber splices were degraded whereas connectors appeared well suited even in terms of power budget. For civil engineering application, standard telecommunication splices revealed too stiff. Yet connectors are likely to degrade because dust size is similar with optical fiber core one. Apart from the interrogation unit, E2000/APC connectors were chosen for eye safety reasons.

Specifity of optical fiber chemical sensors
The major disadvantages of the use of this technology include interference with the ambient light, long term stability and the response time. The response time may be long can it could be determined by the mass transport. A suitable design of the cable and fiber can be useful for decrease the response time. Optical characteristic of the source or detector can change which can have a direct impact on the sensing performance.
Further developments
The radiation-tolerance assessment of components and/or systems includes testing in representative conditions, in terms of dose rate, environment (such as atmosphere, temperature), and operating cycles. These conditions are different for each application. It is well known that gamma radiations also affect the optical properties of optical fiber, like its optical transmission through the radiation-induced attenuation (RIA) phenomena [197]. The amplitudes of this degradation depend on the fiber composition and on the irradiation conditions. Few studies have shown that radiations can also induce change in the Brillouin frequency shift (BFS) of the silica-based optical fibers. Andra launched an R&D program about radiation tolerance inside the thesis of Xavier Pheron.

An essential objective is to establish the metrological performances of the instruments that are installed on site. These must be compatible with the accuracy required for a given mesurande. In particular, the ability of a Distributed Temperature Sensors (DTS) to detect a hot spot on site and measure its actual temperature is a very important feature for many applications. For the end-user, a key performance is therefore the "spatial resolution" of the instruments indicated by the manufacturers in their data sheets. Periodical checks of the temperature readings will also be required on site, in zones that will no longer be accessible after installation. Andra launched an R&D program for metrology. The first result was development of a new cartridge able to check periodically DTS performances was reported

The challenge of optical fibre design is to play with the material of the guide. Core and cladding can be manufactured in different glasses, dopants or materials in order to enhance the performance.

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3.1.3 Wireless Data Transmission

3.1.3.1 Introduction

For certain applications, wireless data transmission can provide advantages for repository monitoring compared to wired systems. A first analysis of the wireless transmission technology is carried out in Table 9 by comparing it with a wired transmission technology, in this case optical transmission.

The main point is that wireless transmission methods are totally non-intrusive with the environment, while the optical system needs physical paths, i.e. optical fibres, for transmitting the light (the information) through the seals.

On the other hand, a wireless system has limitations and shortcomings. In first place, the design and development of a wireless system capable of monitoring the physical parameters inside a repository cell can be an arduous work due to the hard working conditions imposed by both the element itself to be monitored (the canister that is enclosing the radioactive waste), and the environment that is containing it. The electronic devices will work immersed in a harsh environment including high pressure, high temperature, a high degree of humidity, presence of radiation, etc., during an expected lifetime of several decades without any possibility of either being powered from any external source or being replaced in case of malfunction due to the fact that the operating area is sealed to any external manipulation.

Table 9: Wireless vs. Optical transmission media properties comparison

wireless transmission	optical transmission	electrical transmission
non-intrusive	intrusive	intrusive
data transmission only	signal and data transmission	signal and data transmission
large dependency of energy use on transmission distance	small dependency of energy use on transmission distance	small dependency of energy use on transmission distance
data rate on longer distances limited	very high data rates	high data rates
sensors/acquisition units needs autonomous energy supply	simple distribution of energy to sensors	simple distribution of energy to sensors
in case of borehole monitoring, acquisition units/transmitter electronics are located close to the waste	acquisition units/transmitter electronics can be located in safe distance to the waste	acquisition units/transmitter electronics can be located in safe distance to the waste

The main reason to apply wireless technologies is that these methods are non-intrusive and thus have the preference when monitoring has to be conducted behind a safety relevant barrier (e.g. borehole plug, gallery seal or dam), while optical or electrical systems need physical paths, i.e. optical fibres, for transmitting the light or electricity (the information) through the seals.

On the other hand, a wireless system has its limitations and disadvantages. In the first place, when applying wireless systems inside e.g. a repository cell, components additional to the sensors itself have to be installed. Considering the local conditions imposed by both the element itself to be monitored (the canister that is enclosing the radioactive waste), and the environment that is containing it, effort has to be made in order to provide electronic devices that can resist these conditions over longer time periods. The electronic devices have to comply with a harsh environment including high pressure, high temperature, a high degree of humidity, presence of radiation, etc., during an expected lifetime of several decades without any possibility of either being powered from any external source or being replaced in case of malfunction due to the fact that the operating area is sealed to any external manipulation

Another important drawback to take into account is the attenuation of the signal with increasing distance. Due to interaction of the transmission signal with surrounding material, additional attenuation may take place - especially at high frequencies - dependent on environmental parameters like humidity or materials density, and therefore relatively high power may be necessary to get the signal pass through the engineered barriers and seals.

This attenuation is dependent on the frequency utilised, and assessment of the most suitable frequency for the intended application is an important design consideration when designing a wireless monitoring system for a radioactive waste disposal.

The industry offers a wide range of wireless products working in the MHz - GHz range and each one has also limitations especially regarding the penetration capability through solid materials and bandwidth allowable for data transmission, being these two last factors usually inversely proportional. However, each wavelength has different behaviour depending on the antenna construction, environmental conditions, materials composition, etc. that need to be considered, too

In order to get a short overview of the specific features of different frequencies, Table 10 highlights some pros and cons of the high (HF – UHF: 3 MHz to 3 GHz) and low (VLF – MF: 3 KHz to 3 MHz) frequency bands when applied to wireless signal transmission.

Table 10: High and Low frequencies capabilities comparison

High Frequency Wireless Systems (UHF)	Low Frequency Wireless Systems (ULF, SLF, ELF)
Advantages	
Higher data rate/shorter transmission time. Lower power consumption. Small size aerials (shorter wavelength). Wide range of devices available on the market aimed for monitoring applications.	Low attenuation through solid materials/high penetration capabilities. Low attenuationin presence of water or humid environments.
Disadvantages	
Lower penetration capabilities. High attenuation in the presence of water or humidity (especially 2.4 GHz).	Very long wavelength/requires larger antenna sizes. Low data rate. Higher power requirements except for specific developments

For the wireless transmission of data, high-frequency electromagnetic waves are used in many applications, as they can be transmitted easily over long distances in air, but the presence of solid objects (e.g. through engineered barriers) can impede their propagation. The application of high-frequency waves for data transmission in a geologic waste disposal facility is therefore limited to shorter distances (few meters to tens of meters), while low frequencies can be used either in short and long distances. This is further discussed in the following sections.

3.1.3.2 Medium to Long Range Wireless Through-the-earth Data Transmission

When it comes to the wireless transmission of data in a repository over longer distances (>100 m), the large attenuation by the geologic medium makes the application of high frequency waves unfeasible. Here, low-frequency electromagnetic fields in the ELF (Extremely Low Frequency: 3 Hz - 3 kHz) and VLF (Very Low Frequency: 3 - 30 kHz) ranges are more favourable. Low frequency transmission techniques are applied in mine communication and rescue (“trapped miner detection”), cave exploration/communication (“cave radio”) and military communication both on short distance (“rock phone”) and globally (ELF submarine communication). For these applications the used frequency ranges from a hundred Hz to a few tens of kHz. Some examples of low frequency transmission techniques will be described in this section.

For low frequency transmission techniques two principal technical set-ups can be used for the transmitting antenna:

- long, linear grounded antennas
- circular loop antennas

One disadvantage of linear antennas is that the signal strength is proportional to its length times the current. Linear antennas therefore need to be grounded to enable sufficient current flow and the dimensions of linear antennas need to be large. Although this technique is demonstrated to work in principle, it is difficult to prove that the signal propagation is not enhanced by the presence of large horizontal or vertical conducting structures abundant in most mines (e.g. wiring for electricity supply, lighting, communication, pipes, lift cables). Furthermore, the propagation of signals from finite linear antennas is complex to analyse mathematically, making this technique less favourable for a quantitative approach. For these reasons, only the use of circular loops will be developed further in this chapter.

In the following section a short overview will be given on the physical principles of the propagation of low-frequency magnetic fields generated by a loop antenna. On the basis of propagation properties, some relevant boundary conditions for the transmission of monitoring data will be defined. Examples on existing applications will be discussed and in the final paragraph an overview will be given on the current state-of-the-art of wireless data transmission techniques in radioactive waste disposal.

Magnetic wave propagation in a conduction medium

Because of the long wavelengths of low frequency electromagnetic waves, the receiver antenna can be considered to be present in the '*near-field*' of the transmitter in first instance. In that case, the presence of electrostatic fields can be neglected and the physical laws describing static magnetic fields provide an adequate approximation of the field propagation.

A magnetic moment m_d that will be generated by the flow of a current through a loop antenna can be described as a function of the loop area (A), the number of turns of the loop N and the current I:

Equation 3.1.3.2-1

$$m_d = A \cdot N \cdot I$$

Assuming a receiving antenna is in a coaxial configuration in the near-field of the transmitting antenna and is sufficiently small compared to the distance to the transmitter, an approximation of the magnetic field strength H can be made by applying the law of Biot-Savart [198]:

Equation 3.1.3.2-2

$$H\ [A/m] = \frac{m_d}{2\pi\sqrt{(r_l^2 + r^2)^3}}$$

being r_l the radius of the transmitter loop and r the distance between transmitter and receiver. If the transmitting loop is small compared to the distance r, the field strength decreases proportionally to the third power of r.

Besides the decrease of the field strength by increasing distance, interactions with the geologic medium can attenuate the field strength, too. The attenuation of the magnetic waves by interactions with the geologic medium can be characterized by the so-called *skin depth* δ [198], [199]. It can be distinguished between a "good conductor" and a "poor conductor" according to the value of conductivity σ: in case of

Equation 3.1.3.2-3

$$\sigma >> 2 \cdot \pi \cdot f \cdot \varepsilon_o \cdot \varepsilon_r$$

with

- σ conductivity [S/m]
- f frequency [Hz]

ε_o permittivity constant ($8.9 \cdot 10^{-12}$ A·s/V·m)
ε_r relative permittivity [-]

the medium can be considered as a “good conductor”. The skin depth for a “good conductor” can be expressed by

Equation 3.1.3.2-4

$$\delta[m] = \frac{1}{\sqrt{\pi \cdot \mu_o \cdot \mu_r \cdot \sigma \cdot f}}$$

with

μ_o permeability constant ($1.257 \cdot 10^{-6}$ V·s/A·m)
μ_r relative (magnetic) permeability [-]

In case of

Equation 3.1.3.2-5

$$\sigma << 2 \cdot \pi \cdot f \cdot \varepsilon_o \cdot \varepsilon_r$$

the geologic medium can be characterized as a “poor conductor” and the skin depth can be estimated by

Equation 3.1.3.2-6

$$\delta[m] = \frac{2}{\sigma}\sqrt{\frac{\varepsilon_r \cdot \varepsilon_o}{\mu_r \cdot \mu_o}}$$

In absence of paramagnetic materials, μ_r can be assumed to be equal to 1. For ε_r, values around 3 - 80 are reported for geological media, but these are based on high frequency measurements. In case of the frequencies considered for data transmission over longer distances, ε_r, may ranges in the order of magnitude of several 1000 to several 10000 (see MoDeRn Deliverable D-2.3.1 [200]). The conductivity σ of geological media can vary to a large extent, from µS/m to mS/m range for crystalline rock, and mS/m to S/m range for argillaceous rock. The water-filled porosity of the geological media has an important influence on the conductivity ($\sigma_{\text{ground water}} \approx 0.5$ S/m). In case of a repository in argillaceous rock with relevant water content or aquifers situated above the host rock, the transmission path is likely to behave over a large frequency range as a “good conductor”, with the skin depth decreasing with the square-root of the used transmission frequency. Granite or other crystalline rock may - dependent on the conductivity and the transmitting frequency - behave as a poor conductor, which make it possible to consider the use of higher transmission frequencies than in case of argillaceous rock. The attenuation of the magnetic wave by interaction with the geological medium can be approximated by $e^{-r/\delta}$, equivalent to -8.7 dB per skin depth.

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Examples of the application of low-frequency transmission techniques

Mine communication

In mines, low-frequency wireless techniques are applied for in-mine communication and through-the-earth communication to the surface. On the latter technique, much research was performed to investigate the usability of this technology for the rescue of trapped miners in case of emergencies. Two principal uses of wireless systems for rescue of trapped miners can be distinguished: 1) locating of trapped miners and 2) communication with trapped miners. Early experiments in the nineteen-thirties indicated that through-the-earth communication was principally possible, but due to the lack of proper technology that can meet the hardware requirements, it took until the seventies before the development of such systems started [201]. For the location of trapped miners, mobile systems were developed that were powered by the miner's cap lamp battery. The transmitter consists of a horizontal single- or multiple-turn loop, either mobile or preinstalled (i.e. around pillars). By using a horizontal loop, a null in the horizontal magnetic field appears directly above the transmitting antenna, enabling to locate the trapped miner. Successful tests were performed in a number of mines (coal and hardrock). Based on a single-turn loop with a diameter of 8.7 m and using frequency between 1 kHz and 3 kHz, the system was found to work reliably over a distance of 180 m [201]. From Murphy and Parkinson, (1978) [202] it can be estimated that for this application about 30 to 50 W must be fed into the antenna.

Another example of wireless communication to the surface is a system which has been developed for refugee shelters, enabling the bi-directional communication with the surface by use of a keyboard [202]. The installation is based on a 38 m-diameter loop antenna with a power input of ±10 W. The company *Mine Site Technologies*[3] developed a one-way text messaging system called *PED* (Personal Emergency Device) to transmit messages to miners. The PED system makes use of large antenna loops (150 - 3000 m diameter, dependent on local conditions), feed with about 1.2 kW electric power.

Military communication

For military communication with submarines, ELF transmitters are used with long vertical, partially grounded antennas of 60 to 150 km length to send signals in the frequency range of 20 - 200 Hz [203]. Not much is known about these ELF transmitters, but to be able to cover large parts of the earth surface, the energy consumption of this installation can be assumed to be in the order of magnitude of 100 kW or more.

On shorter distance, mobile so called "Rock Phones" are developed, which enables the communication by text messaging or two-way voice transmission from caves, tunnels and large building structures [204]. The transceiver uses a 3.8 m diameter loop, and works at frequencies around 5 kHz. As maximum reception range, a distance of 200 m is given. The used data frequency is 30 bits/s, but can be increased to 3000 bits/s on shorter distances to enable voice transmission. The energy consumption is about 170 W.

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Application of low frequency magnetic waves in radioactive waste disposal

Each of the techniques discussed in the previous section is optimized for the particular application. In case of the transmission of monitoring data from a radioactive waste repository to the surface, a number of specific boundary conditions for the application of wireless technique can be defined:

- fixed antenna locations exists and the transmission path and distance is known
- the transmission properties of the host rock and overburden are invariable and known
- there are no restrictions for the antenna geometry and size in case of a horizontal loop-antenna set-up
- localized sources of interference, both underground and on the earth's surface, can be eliminated or optimized
- no specific timeframe for data transmission is needed
- only low transmission bandwidth are necessary
- a reliable transmission of data is essential
- energy use is a relevant topic

For the transmission of monitoring data out of a repository, the energy efficiency can be assumed as the most important design criteria in case of the long-term monitoring of a radioactive waste disposal in the post-closure phase. Although some potential techniques may exist either to convert energy in the disposal facility or to transmit energy by wireless techniques into the facility, on basis on the current state of technology it is reasonable to assume that the transmission equipment will be supplied by batteries.

The energy-efficiency depends mainly on two factors:

- energy content per bit of transmitted data
- amount of data that needs to be transmitted

The energy content per bit can be improved by refining the transmission equipment and set-up. The amount of data that needs to be sent can be decreased by analysis of the data need, e.g. the necessary intervals of data transmission, the precision of the transmitted data or the kind of information that needs to be transmitted.

State-of-the-art of low-frequency transmission techniques in waste disposal

In this section, an overview is given on the present state-of-the-art of low-frequency based transmission techniques for the transmission of monitoring data out of a geologic waste disposal. Additional, experimental results of propagation experiments performed in the HADES URL for other purposes will be discussed, too.

<u>RWMC - integrated set-up for medium to large distance transmission in crystalline rock</u>

Since 2002, RWMC is working on wireless data transmission systems as part of their monitoring system that is being developed to support decision-making for geological repository closure

[205], [206]. RWMC considers the use of low-frequency magnetic waves for data-transmission on several scales through crystalline rock or EBS components (e.g. bentonite). For the research and development of low frequency wireless monitoring systems, three types of concepts were designed:

- Short-range transmission (from 5 m to 30 m)
- Middle-range transmission (from 30 m to 100 m)
- Long-distance transmission(around 300 m)

The technical requirement of each transmitter differs, dependent on the transmission distance, the measured parameters, the arrangement of each transmitter and their condition. RWMC's wireless technology is based on the use of very low frequency electromagnetic waves as a carrier wave (around 1 kHz and 10kHz). The specifications are given in Table 11.

The integrated, bi-directional system consists of digitized and very reliable transmitter- and receiver-units (Figure 84). The subsurface transmitter unit contains a flexible multi-channel data logger, enabling to connect up to 19 sensors to this system. For the chassis of the data transmission unit a polyvinyl chloride (PVC) cylinder is used. The system can accumulate data before transmission to save electric energy. The transmission speed is 75 bits per second. Data acquisition and the transmission of data by the transmitter unit can be managed by a (surface based) controller unit.

Table 11: Typical specifications of pore water pressure sensors and total pressure sensors

Transmission distance	Approximately 100 m (in crystalline rock)
Transmission period	Maximum 20 years (4 measures/day, 1 transmission/week)
Battery	Lithium battery
Carrier frequency	Around 1 kHz
Transmission velocity	75 bps
Channels for sensors (Number of sensors)	19 channels

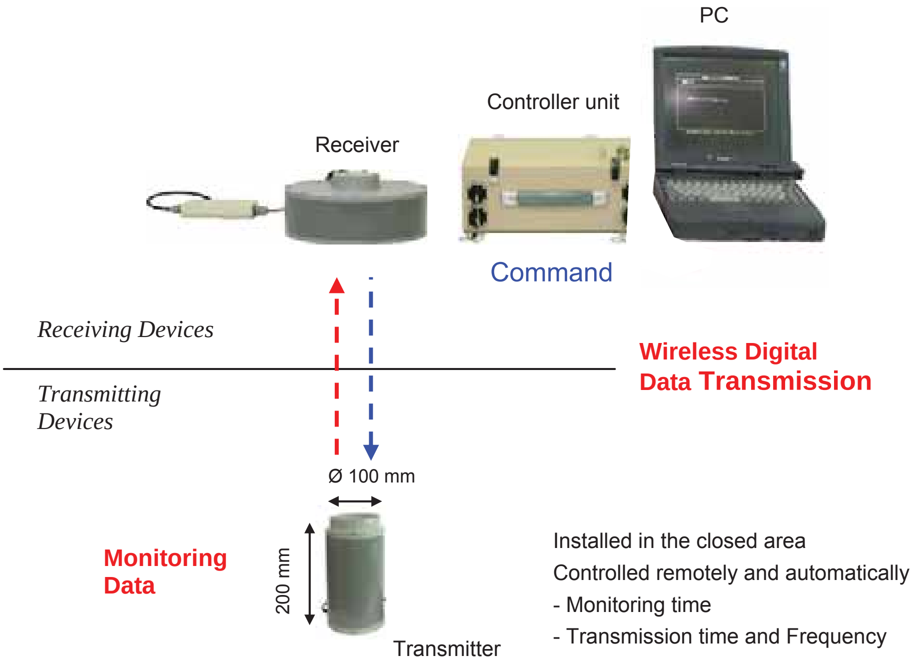

Figure 84: General set-up of the RWMC Wireless transmission system

The long-distance transmission system of RWMC should connect the access tunnel to the surface (±300 m) and make use of a 5 m diameter loop antenna (Figure 85). In 2002, RWMC established signal transmission over 150 m of crystalline rock at the Äspö HLR test site by the 0.1 m diameter loop antenna shown in Figure 84 [207] and has demonstrated that in the absence of long conducting structures, propagation was close to the expected values. Further researches and experiments are ongoing (see below).

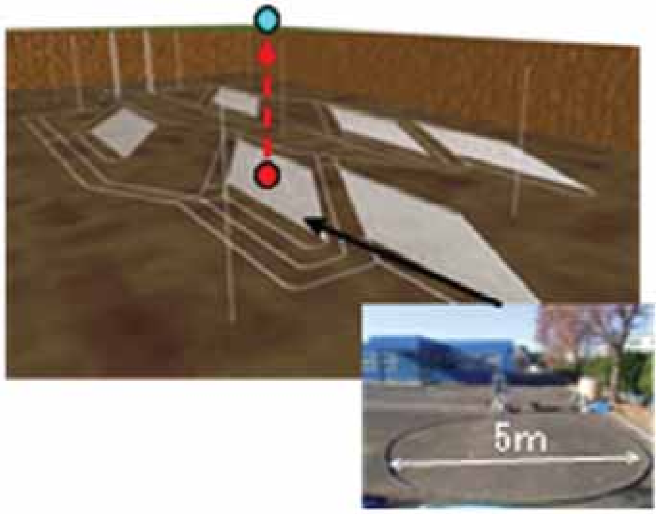

Figure 85: RWMC Wireless transmission system for long-distance

RWMC has carried out a stepwise research and development plan since 2002 including:

(A) Evaluation of VLF electromagnetic wave propagation,

(B) Efficient transmitting method, and

(C) Efficient receiving method.

With respect to (A), attenuation characteristics of VLF electromagnetic waves in crystalline rock were confirmed and its evaluation method was established from 2003 to 2005. With respect to (B) and (C), through various experiments with the transmitting and receiving antenna, basic data which are necessary for the optimum design of the wireless transmission system were acquired in 2006 and 2007. Since 2008, in-situ demonstration of wireless transmission of monitoring data through a bentonite buffer surrounding the waste containers has been carried out.

An overview of the RWMC research plan is given in Figure 86. The RWMC experiences on short ranges are discussed in more detail in section 3.1.3.3.

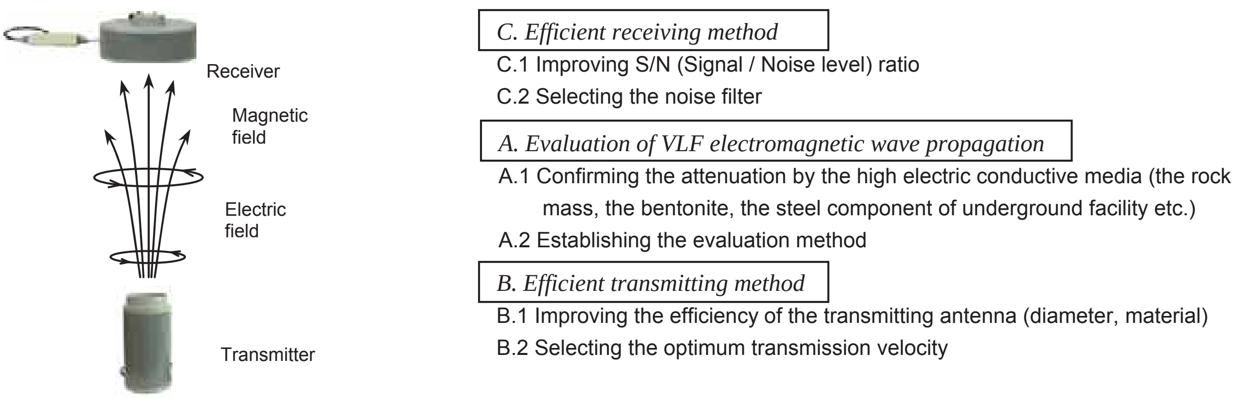

Figure 86: RWMC Outline of research and development

MISL - test of military communication equipment in the HADES URL

The Canadian company MISL performed in 2005 a number of tests of their equipment in the HADES URL [208]. The equipment used was intended for military purpose. Signals were transmitted from the surface to the HADES URL, using antennas of 2 m and 9.1 m diameter (magnetic moment ±2000 A·m^2). It was found that the field strength decreased according to Equation 3.1.3.2-2, with signal attenuation up to 10 dB. A strong influence of the location of the transmitting antenna was recognized, and shows a distortion of the field propagation by steel components in the HADES URL (e.g. floor grids). Transmission frequencies were not reported and no information was given on the data transmission achieved.

NRG - experiments on magnetic wave transmission in the HADES URL

Since 2010, NRG performed several test on the propagation of low-frequency magnetic waves as part of the current MoDeRn-project, focussing on characterizing and optimizing the energy use of the technology. The first experiments were performed in 2010 and made use of a 3.5 m octagonal loop antenna (magnetic moment ± 2500 A·m^2) placed in the HADES URL. Signal transmission was achieved over a distance of 225 m at several frequencies around 1 kHz. In 2011 and 2012, experiments were performed in order to characterize the propagation behaviour and improve the energy efficiency of the set-up. In 2012 and 2013, data transmission experiments were performed demonstrating that data can be sent with energies of 1 Ws per bit of transmitted data. Data rates of 100 sym/s were achieved. For more information see MoDeRn Deliverables D-2.3.1 [200] and D-3.4.2 [209].

MISL/Nagra - experiments on magnetic wave transmission in the Grimsel test site (GTS)

MISL performed in 2005 a number of performance tests at the Grimsel test site [210] as part of the Nagra experiments on wireless data transmission over a shotcrete plug. Several transmission experiments were performed, using loop antennas of 9.1 m and 2.0 m diameter (max. magnetic moments ±2146 A·m^2 and ±248 A·m^2, respectively). The signal was able to penetrate through ~80 m granitic overburden and a maximum of ~250 m horizontal distance. A test with 2 m loop antenna (±150 A m^2) and indigenous batteries functioned reliably with both transmitter and receiver inside the GTS up to 380 m horizontal distance. The latter test functioned more reliable because hydro electric transmission lines located near the access tunnel created in-band interference in the transmission system. Transmission frequencies were not reported.

Since 2007 the TEM consortium collects data from six sensors via a wireless data transmission experiment at the GTS [211]. The transmitter with a diameter of 220 mm is buried in a small borehole behind a 1 m bentonite buffer and 4 m shotcrete plug. Using a carrier frequency of 575 Hz and powered by a battery, 8 data packets are transmitted every 12 hours over a distance of ~30 m.

The above-mentioned research efforts on wireless data transmission on large distance (>100m) are summarized in the table below.

Table 12: Overview on current experience on wireless data transmission on large distance (>100m)

Organization /country	host rock /overlying rock	purpose of installation /experiments	experimental conditions	max. distance	results
MISL (Canada) at HADES URL	Boom Clay (45 m) sandy aquifer (180 m)	test of battery-supplied military communication equipment	9.1 m loop antenna, coaxial constellation, top-down constellation (receiver in HADES)	225 m	signal transmission was achieved; signal attenuation* was about 10 dB**
NRG (Netherlands) at HADES URL	Boom Clay (45 m) sandy aquifer (180 m)	experimental measurement within MoDeRn	3.8 m loop antenna, coaxial constellation, 500 Hz to 5 kHz	225 m	signal transmission up to 2 kHz was achieved, data transmission was achieved up to 100 sym/s, energy use was ±1 Ws/bit
RWMC at Äspö HLR test site	crystalline rock (100 m)	full bi-directional demonstration set-up for wireless data transmission, including analogue sensor inputs, data acquisition unit, power supply	0.1m loop antenna ±1 kHz (and ±10 kHz)	150 m	signal transmission around 1 kHz was achieved; under undisturbed conditions, propagation was close to theoretical value
MISL/Nagra at Grimsel Test Site	crystalline rock (80 m) main access tunnel (100-250 m)	test of battery-supplied military communication equipment	9.1 m loop antenna, top-down constellation (transmitter at surface, receiver in access tunnel)	380 m	signal transmission was achieved; signal attenuation estimates were near the error bounds (1.8 ±1.8 dB) **

* attenuation by geologic medium may be higher (distortion of field by steel components of the HADES URL)
** transmission and data frequency unknown

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3.1.3.3 Short Range Wireless Through-the-earth Data Transmission

This section provides an overview of the different aspects to be considered when designing a short range wireless data transmission system. The description in the first part is based on high frequency data transmission, and in the second part, short distance transmitters based on low frequencies are described.

System Overview

The main goals to be achieved when designing a short range wireless monitoring system are the following:

- To measure the physical parameters inside the repository cells, i.e. pressure, temperature, humidity, etc.
- To transmit this information up to a safe area outside the disposal cell using a non-intrusive method and always keeping the safety of the disposal facilities.
- Once the information has been sent out, the system must be capable of processing and displaying it on a terminal display and/or re-sending it to a third monitoring system, for example, a surface control room.

- In addition, it would be advantageous if the system is intelligent enough to detect possible sensors failures or wrong measures, so it will be capable of performing self-diagnostics or similar procedures.

Figure 87 shows an overview of a wireless monitoring system. The sensors are located inside the sealed area, within a buffer or backfill, and periodically send their information to a receiver located in a safe zone behind a sealing element (e.g. a thick concrete wall). In addition, more sensors could be embedded in the rock.

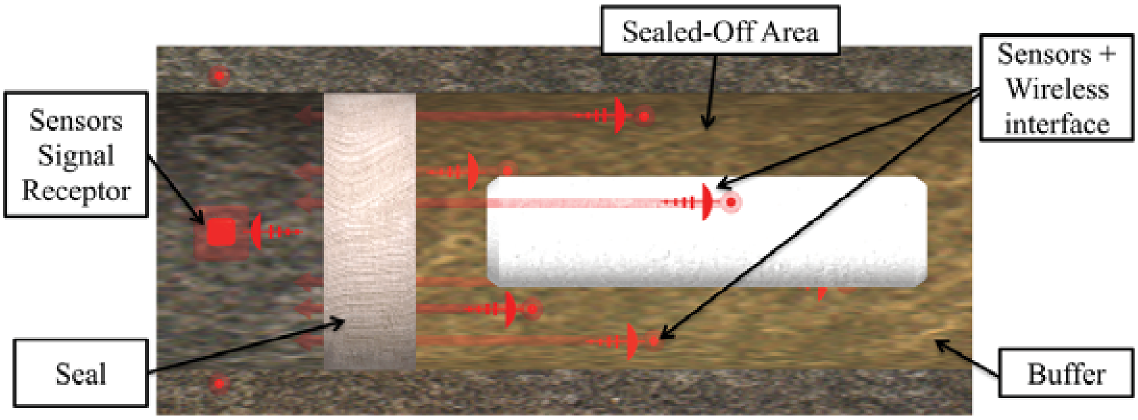


Figure 87: Overview of a wireless monitoring system elements distribution

In order to achieve the abovementioned objectives and obtain a suitable monitoring system for a radioactive waste disposal, the following key points have been analysed:

- Transmission technology (transmission media).
- Communication protocol.
- Power sources.
- Environmental conditions.
- Sensors.

In the following sections, these key points are discussed.

Transmission technology

One of the main advantages of high frequency is the higher data rate capability in comparison with lower frequency bands, as it means shorter transmission times and lower power consumption. On the other hand, on longer distances, signal attenuation by solid materials may outlevel the advantages of higher data rates, and low-frequency techniques as discussed in previous section might be more energy efficient [213].

Many devices aimed for monitoring applications based on high frequency systems are available on the market, featuring a very small size, very low power requirement, low cost, etc. These factors and the positive experiences using devices working in the UHF band, gained in previous European research and development projects as RAINOW [217] point at the UHF band as suitable for developing a wireless monitoring system.

In order to reduce the constraints imposed by the penetration capabilities, two improvements or solutions can be implemented. The first one consists of installing embedded radio signal repeaters inside those sealing elements that may block radio signals. Another alternative, more bulky but on the other hand powerless, is the installation of so-called "waveguides" inside the sealing elements, but without passing through completely. These waveguides, made of an electrically conducting material, minimise dispersion and signal loss. Figure 88 shows an illustration of both methods.

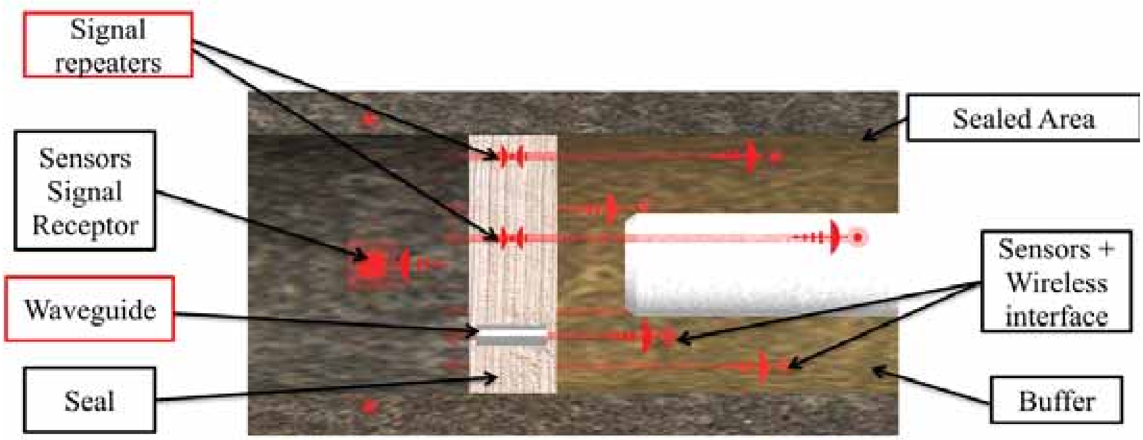


Figure 88: Signal repeaters and waveguides installed inside the sealing element

UHF band frequency selection

There are three sub-bands assigned for ISM purposes (Industrial Scientific and Medical) within the UHF band. These bands are free of fees (no licenses are needed) and the commercial devices that operate in those bands are factory adjusted and calibrated to accomplish the transmission power limits established in the ITU (International Telecommunication Union) radio regulations.

These ISM frequencies in the UHF band assigned to Europe are 433 MHz, 868 MHz and 2.4 GHz. The main advantages between the 2.4 GHz band and the other frequency bands are higher data rates (up to 250 kbps for application based on WSN: Wireless Sensor Network) and a short wavelength (12,5 cm approx.), which makes it suitable for using wave guides or performing transmission though confined spaces. However, the presence of water or humidity causes very high attenuations at these frequency bands and consequently reduces the maximum transmission distance.

Table 13 compares the attenuation of the selected frequencies through different materials, showing that attenuation of 2.4 GHz is always higher than at lower frequencies in all kinds of materials, and becoming insurmountable in presence of fog or rain in air.

Table 13: Attenuation comparison of the selected frequencies through different propagation media

Propagation media	433 Mhz		868 Mhz		2.4 Ghz	
	Loss	Attenuation	Loss	Attenuation	Loss	Attenuation
Open office	0 %	0 dB	0 %	0 dB	0 %	0 dB
Window	< 5 %	< 1 dB	15 %	1 – 2 dB	30 %	3 dB
Thin wall (plaster)	25 %	3 dB	35 %	3 – 4 dB	50 %	5 – 8 dB
Medium wall (wood)	40 %	4 – 6 dB	50 %	5 – 8 dB	70 %	10 – 12 dB
Thick wall (concrete)	50 %	5 – 8 dB	60 %	9 – 11 dB	85 %	15 – 20 dB
Armoured wall (reinforced concrete)	70 %	10 – 12 dB	80 %	12 – 15 dB	90 %	20 – 25 dB
Floor or ceiling	50 %	5 – 8 dB	60 %	9 – 11 dB	85 %	15 – 20 dB
Armoured floor or ceiling	70 %	10 – 12 dB	80 %	12 – 15 dB	90 %	20 – 25 dB
Rain and/or Fog	90 %	20 – 25 dB	95 %	25 – 30 dB	?? *	?? *

Althought 868 MHz and 433 MHz frequencies have lower data rate capabilities (20 Kbps for 868 MHz), this bandwidth should be enough for fulfilling the expected requirements for a radioactive waste disposal, as the system will only need to send a datum once per day or even once per week, so they are clearly a better choice than 2.4 GHz. Furthermore, 868 MHz presents a shorter wavelength (34.5 cm approx.), which is also suitable for using waveguides, so *a priori* this frequency is considered as the most suitable one to be used in the system.

Communication protocol

The selection of a suitable protocol to establish the communication between the different electronic devices of the system could contribute to get a more flexible configuration, open to the association of other elements in the future and capable of detecting and solving possible communication errors. Three possibilities have been considered:

- ZigBee protocol:
  This well-known protocol was developed based on the standard IEEE 802.15.4 in 2004 [212]. Aimed for the implementation of WSNs (Wireless Sensor Network), this stack has spread through several commercial and industrial fields in the last years and a wide range of products has been developed using this technology. Some of the highlighted features are the following:
    - Specially designed for WSN (Wireless Sensor Networks) applications.
    - Based on the standard IEEE 802.15.4.
    - Auto-routing capabilities.
    - Low power end devices (only some μA of consumption during power save modes).
    - Up to 64K nodes management under the same network.

  Although ZigBee fulfils practically all the application requirements, its great amount of capabilities call for a relatively high data rate for transferring information between the network devices and requires an efficient power management. ZigBee modules are available in the market including the radio transceiver working both at 2.4 GHz and 868 MHz. However, the latter is not the most appropriate one for this protocol given its lower bandwith and the amount of information to be transferred, as the transmission time and consequently the average power consumption would increase noticeably.

- Proprietary protocol:
  The development of a custom-built protocol for this specific application is the best option for fulfilling all the requirements both from the point of view of power consumption, network management, data transference, etc. The implementation of a specific protocol for the application would call for lower hardware resources than any commercial stack (which has been developed to be adapted to a wide range of purposes), obtaining lower power needs and lower hardware costs. However, a custom protocol means that the system is closed, i.e. any other product of an external vendor could not use the same wireless network, limiting the expandability of the system to future services.

- Intermediate solution:
  In view of the need of a “less powerful” protocol than ZigBee but open to the integration of future services or another vendor system, some technology companies offer to the customer the possibility of making his own software stack based upon the standard IEEE 802.15.4. This solution would consist of the basic ZigBee stack, being the main difference with “standard” implementations that the customer will add to the base only the functionalities needed for his

application. Therefore, the processor that runs the stack will be dedicated just to the management of the algorithms designed for this specific system instead of processing the whole ZigBee stack, which includes a great amount of unused functions.

This means that the system developed using this technique would have the following features:

- Open network for future services (it is based on the standard IEEE 802.15.4, the same of ZigBee).
- Lower capabilities than ZigBee but enough for the target application (it is not expected to have 64K sensors in the same cell).
- Lower bandwidth requirements, suitable to work using 868 MHz radio systems.
- Lower hardware resources needed means lower power consumption, lower hardware cost, etc.
- Royalty free.

Power source

Regarding the question of how to provide energy to power the devices inside the cell, two main options can be considered. The first one, and also the easiest to be implemented, is the use of long lifetime batteries integrated in the devices. Using Lithium Thionyl Chloride ($Li\text{-}SOCl_2$) chemistry [214], which has a very high energy density as well as a wide operating temperature range and a very low self-discharge (lower than 1% per year), a proven lifetime longer than 25 years for the wireless nodes was achieved [215].

The second option is to obtain the energy from an external source to the device. There are two possibilities; i) the harvesting of energy from physical or chemical gradients inside the cell, as temperature or radiation and, ii) the wireless transmission of energy to the cell using e.g. microwaves or high power light (inserting a light guide along the seals). However the insertion of any element in this critical part needs a careful study on the effects on the sealing properties.

Environmental conditions

The electronic devices should be designed to withstand the harsh environmental conditions inside the cell, including high pressure, high humidity and temperature levels, etc. Although these factors are present in other fields in the industry where monitoring systems are already installed (e.g. mines, public works, oil industry, etc.), the presence of radiation in the monitoring scenario imposes additional difficulties.

The α- and β-radiation emitted by the radioactive waste is blocked by the canister shield. However, a great amount of γ-radiation passes through it (up to 60mSv/hr). Although this kind of radiation is less ionising than the others, its effects should be taken into account especially for devices working under long term exposure.

According to the former, the radiation is capable of detaching electrons from atoms (thus ionising them). Consequently most of the existing commercial electronic devices are not suitable for these working conditions, at least without having any kind of protection/shielding. The most sensitive components are those based on MOS technologies and unfortunately, these are practically the totality of the microelectronic circuits used nowadays, as microprocessors, RAM memories, transistors, etc. In these semiconductors structures a dose rate strong enough can cause the continuous activation of the conducting channel, producing the activation of the MOS element and losing control over it.

In order to avoid or minimise the effects of the radiation over this kind of devices, two solutions can be implemented. The first one implies the use of special electronic components originally intended for other fields where ionizing radiation is also present, and for which they are specially designed and protected. This is the case of military and spatial applications [216] but the high cost of these devices makes it advisable to use other techniques such as the protection of the electronics by means of shields made of lead or steel. This second option can increase the height and volume of the device but also implies an important cost reduction.

On the other hand, the fact of having a certain level of ionizing radiation inside the operating area also opens up a new research line to be taken into account; can the ionizing effect be used for harvesting energy and powering the inner cell electronic devices? This issue may be addressed in the near future.

<u>Sensors</u>

Finally, some basic guidelines must be taken into account when selecting the kind of sensor element to be installed in a high frequency based wireless monitoring system, regardless of the parameters to be measured. The first one is that the sensors should give accurate readings on the long term without recalibration. In addition, the selected elements must withstand a wide range of temperature and humidity conditions and also allow the assembly of a protective shield against radiation.

Each wireless node should be capable of powering and reading the measures of several sensors (at least three), performing a provisional analysis of the signal and detecting possible measurement failures, and repeating the process when necessary. Figure 99 shows a possible block diagram of a wireless node including the sensor elements.

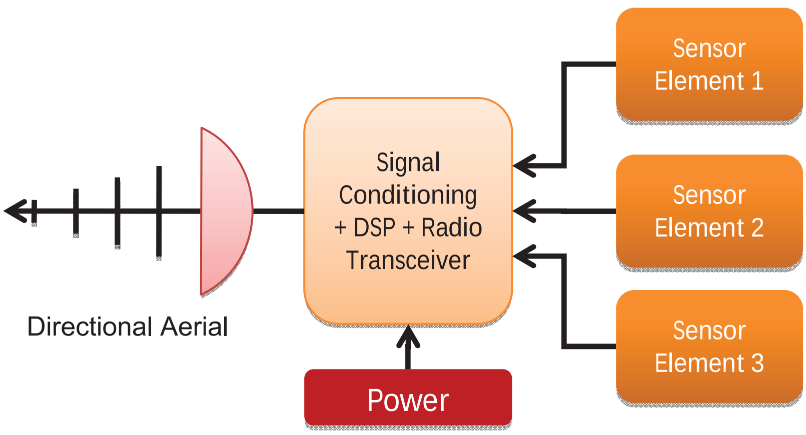


Figure 89: Wireless node blocks scheme

Experiences

<u>AITEMIN – high Frequency wireless transmission for short distance transmission through concrete and crystaline rock in the Grimsel test site (GTS)</u>

As part of the current MoDeRn-project, and based on the former premises, AITEMIN is carrying out since 2010 the design, development and test under "real conditions" of a new high-frequency short-range wireless transmission system, capable of monitoring the physical parameters inside a repository. The system developed comprises 5 units that integrate both the wireless node and three sensors within compact, sturdy cilyndrical housings, ready to be inserted in boreholes.

The units were inserted into horizontal boreholes measuring 80 mm in diameter, excavated in a 4 m long concrete plug sealing a gallery in the GTS (see Figure 90). Two of the units remained in the bentonite placed at the other side of the plug, and another two in the concrete mass. The fifth one was inserted in the surrounding rock. All the boreholes were sealed after the units' insertion, and a receptor was placed outside the plug, connected to a master acquisition unit. The system proved to work satisfactorily, so that data have been successfully acquired since the installation in 2011. More information can be found in MoDeRn Deliverable D-2.3.1 [200].

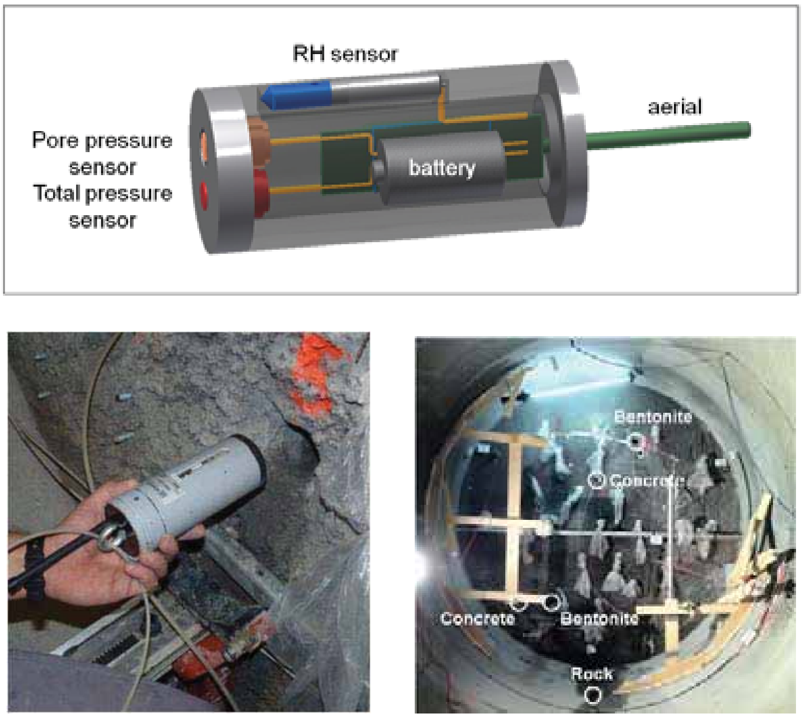


Figure 90: Practical implementation of a wireless system inside engineered barriers of the disposal system

In paralell to the former, AITEMIN is applying since 2010 the wireless system in project SEALEX, run by the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) of France [219]. This project, carried out in the clay-rock underground research laboratory of Tournemire, France, comprises six independent tests running in parallel. Each test consists of a 1.2 m long plug made of compacted bentonite and inserted into a 0.6 m diameter horizontal borehole (see Figure 91). Each test features a plug with a different construction configuration for comparison purposes, e.g. cylindrical blocks, circular section shaped blocks, bulk material, etc. A closure system serves to confine mechanically and hydraulically each plug providing as well an artificial hydration system to help reach saturation state in the short term.

Five of the tests are equipped with wireless nodes embedded in the bentonite. Five nodes are installed per test, managing up to four sensors each, measuring total pressure, pore pressure and relative humidity (see Figure 92).

For each test, a wireless receiver, installed in a side borehole excavated in the rock, gathers data from the nodes, at a rate of one reading per day. At this rate the node batteries are expected to last several years. Each receiver is cabled to a Master Unit that manages the nodes and displays and sends the data from the sensors to the Data Acquisition System. Figure 93 shows the appearance of one of the blocks with an embedded wireless node, corresponding to a plug constructed with pre-compacted bentonite blocks, and the instrumentation and nodes fixed to the rock before the emplacement of bentonite, corresponding to a plug constructed with bentonite pellets and powder.

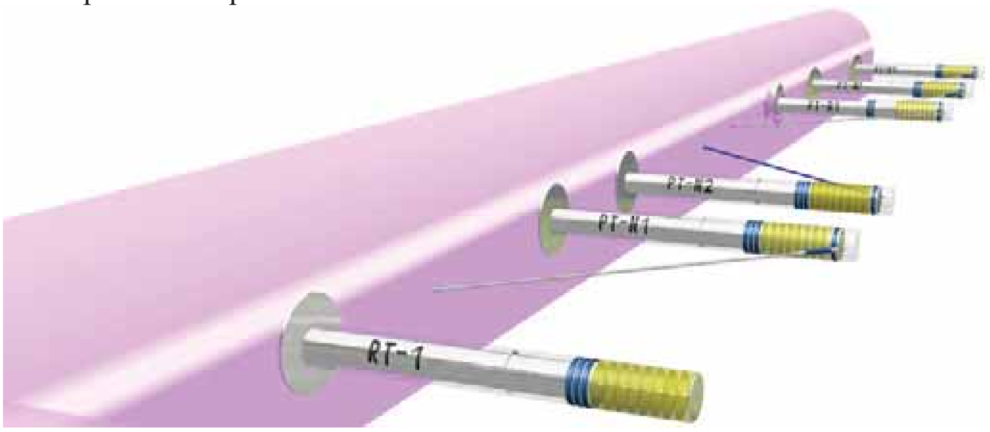


Figure 91: General layout of the SEALEX project.

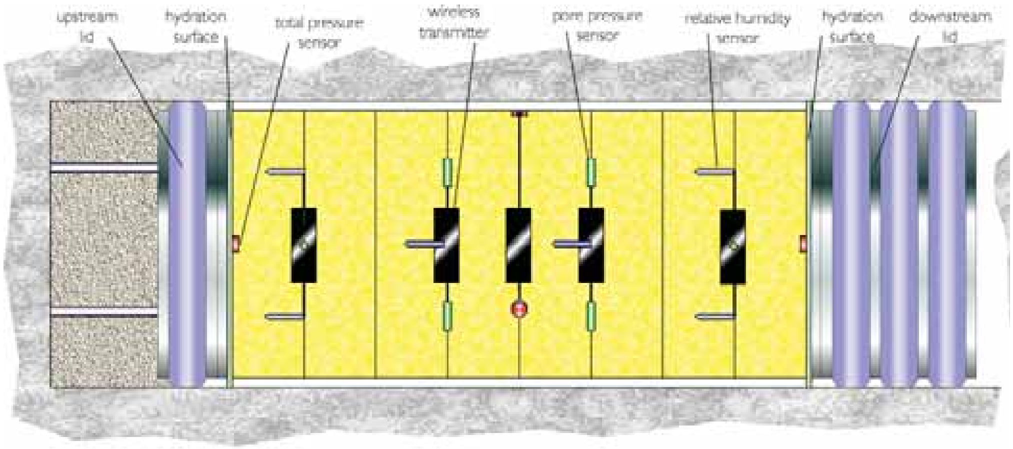


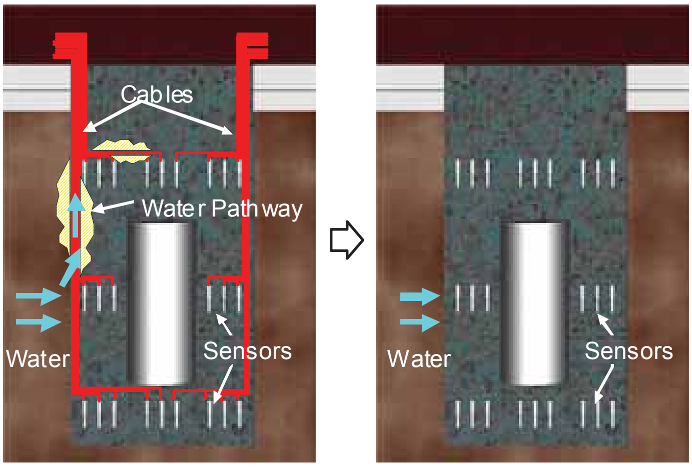
Figure 92: Layout of one of the tests, constructed with pre-compacted blocks.

Figure 93: Appearance of node embedded in bentonite block made of four sectors (left) and nodes and instrumentation secured to the rock prior to fill up with bentonite pellets and powder (right).

RWMC – low frequency integrated set-up for short distance transmission in crystalline rock

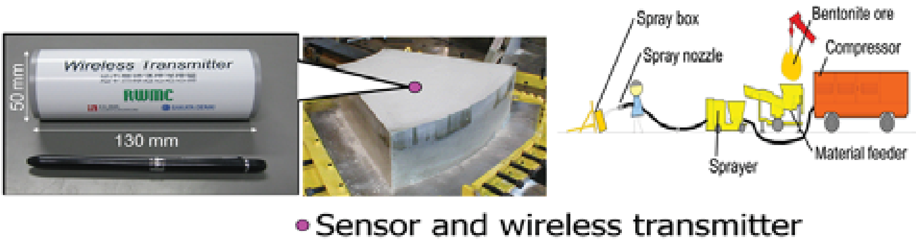
In addition to the equipment described in section 3.1.3.2, RWMC has developed in 2010 a smaller wireless transmitter (diameter 48mm) based on low frequency waves for use in buffer materials (Figure 94b), with built-in temperature sensors and other external sensors [207]. Transmission distance is approximately 20 m in the soil and crystalline rock.

The short range transmission system from 5 m to 30 m was developed for measuring characteristics of the inside engineered bentonite barrier system. They allow the non-intrusive monitoring and are easy to arrange compared to conventional electric or fibre optic cables (Figure 94a). An installation method has been developed, which allows the placement of the wireless transmission system with the shotclay technique. This method does not loosen buffer materials around instruments (Figure 94b) [207].



7

(a) Avoiding the disturbance of barrier by transmission cables

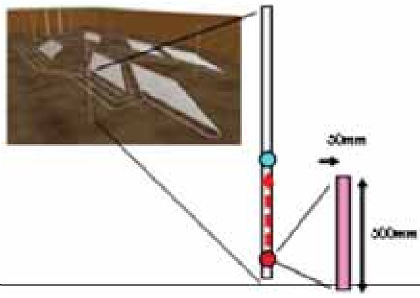
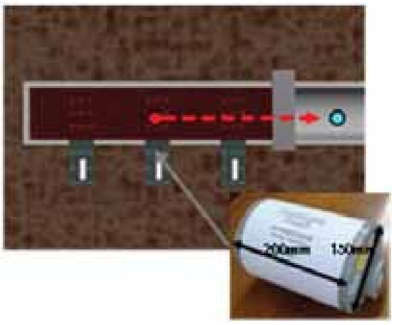


(b) Simplified installation with the shotclay technique

Figure 94: Practical implementation of a wireless system inside engineered barriers of the disposal system

Table 14 summarises features of the short range low frequency transmitters developed.

Table 14: Summary of features of the RWMC short range wireless transmitters

Performance	Figure of transmitter	Objectives
Size:100 mm × 50 mm ø Transmission distance: 20 m Number of sensors: 1 internal +1 external sensor Power supply: Lithium batteries Data rate: 75bps		Repository based monitoring From buffer to top of the cap
Size:200 mm × 50 mm ø Transmission distance: 20 m Number of sensors: 1 or 2 external sensor Power supply: Lithium batteries Data rate: 75bps		Repository based and borehole based monitoring From buffer, seals or backfill to borehole
Size:200-350 mm × 200mm ø Transmission distance:~30 m Number of sensors: 10 sensors (1.2kHz / 8.5kHz) Power supply: Lithium batteries Data rate:75bps		Repository based and borehole based monitoring From seals to access tunnel

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3.2 Borehole-based monitoring

In-situ (repository-based) monitoring provides more accurate and more reliable information on the actual status of the repository than a more remote monitoring. In particular in-situ monitoring provides the ability to monitor local waste emplacements, individual disposal cells or barriers such as seals (see Section 3.1.). However, this type of monitoring is usually intrusive in the sense that it requires electrical cables that connect locally-placed monitoring sensors with external devices for data gathering. The need to pass these cables through seals may affect the integrity of the seals. Alternatively, one may employ wireless sensors (see Section 1.2.1), but there are still significant technological developments required, before in-situ wireless sensors can be utilised.

Borehole-based monitoring techniques allow sensors to be installed in the immediate vicinity of, for example, a disposal cell (i.e., as close as possible without impacting the integrity of the disposal design). They are thus non-intrusive, but they still have the potential to provide information about changes within the repository. The indirect nature of non-intrusive measurements for determining physical or chemical parameters without directly accessing the targets of interest, could constrain the accuracy and reliability of non-intrusive techniques. Using suitable combinations of several techniques is expected to improve the reliability of borehole-based monitoring.

In this section an overview of potentially useful borehole monitoring techniques is provided. Further details on all the methods presented in this report can be found in textbooks [220], [221], [197], [238], [239]. Therefore, only the key features of the individual techniques are described with an emphasis on their application to monitoring in radioactive waste repositories.

3.2.1 Near field geophysical techniques

This type of geophysical technique requires only a single borehole and can be performed at any depth range (i.e., it is independent from the distance to the surface), and sense the properties of the borehole itself and its immediate vicinity (i.e., from a few centimetres to about one metre).

See [220] for more detailed descriptions of these main techniques.

- *Borehole televiewer (optical)*
  - Image the borehole walls using a 360° camera
  - Allow fracture orientations to be determined
  - Can be operated in dry and with some limitations in water-filled holes

- *Caliper logs*
  - Determine variations of the borehole diameter using calliper arms
  - Required for the calculation of correction factors of density logs
  - Allow zones of potential weakness to be identified and conclusions on principal stress direction can be drawn
  - Can be operated in dry and water-filled holes

- *Resistivity logs*
  - Determine electrical resistivities with galvanic coupled measurements
  - Useful technique for determining a variety of lithological parameters
  - Usually requires boreholes to be water-filled.

- *Electromagnetic induction logs*
  - Determine electrical resistivities with inductive measurements
  - Useful technique for determining a variety of lithological parameters
  - Can be operated in dry and water-filled PVC-cased and uncased boreholes

- *Gamma logs (passive)*
  - Provide fine grain fraction estimates by measuring natural gamma ray emission
  - Useful for determining clay and silt content
  - Can be operated in dry, water-filled, cased and uncased boreholes

- *Gamma logs (active)*
  - Provide density estimates by gamma ray emission of a radioactive source
  - Useful for determining density and porosity
  - Can be operated in water-filled, cased and uncased boreholes

- *Neutron logs*
  - Identify the presence of water in a formation using a neutron emission source
  - Useful for determinations of porosity and water saturation
  - Can be operated in water-filled, cased and uncased boreholes

- *Nuclear magnetic resonance (NMR) logs*
  - Identify the presence of water in a formation by exciting the spin of water molecules
  - Useful for porosity and permeability determinations.
  - Can be operated in dry, water-filled, PVC-cased and uncased boreholes

- *Sonic logs*
  - Determine elastic formation properties by exciting and receiving high-frequency seismic waves
  - Useful technique, for example, for testing the mechanical integrity of the formation
  - Complement surface-based seismic measurements
  - Can be operated in dry, water-filled, uncased boreholes

- *Borehole gravity*
  - Determine density by measuring the gravitational attraction
  - Complement surface-based gravity measurements
  - Can be operated in dry, water-filled, cased and uncased boreholes

These techniques are not expected to image the interior of a repository, but they determine the near-borehole structures with a high accuracy. Therefore, they are judged to be useful for correcting systematic borehole effects that may occur in other data types, which have the capability to characterise structures further away from the borehole.

3.2.2 **Far field geophysical techniques**

These methods provide information up to greater distances (i.e., from a few metres up to a few tens of metres).

3.2.2.1 Single-hole methods

- *Single-hole geoelectric tomography*
  Electric currents are injected through a pair of electrodes into ground and the resulting electrical potential differences are measured with another pair of electrodes. A standard multi-core geoelectrics cable can be employed as an electrode string. The method requires the boreholes to be uncased and water-filled.

  Data are analysed with standard 2D electric resistivity tomography (ERT) codes. Depending on the geological situations 2D analysis provides a good approximation, although the general situation of data recorded in a borehole requires a solution for full space. Compared with near-field electrical wireline logging, single-hole geoelectric tomography provides a much better penetration depth. Depending on the length of the electrode string, several tens of metres lateral penetration can be achieved. An example of the method is given in [222].

- *Single-hole georadar*
  This technique uses an electromagnetic source, and requires transmitter and receiver antennas to be placed in the same borehole. Both antennas are moved at a constant offset along the borehole. Typical antenna frequencies range from 20 MHz to 1000 MHz. The direct wave travelling from the transmitter to the receiver antenna provides information about the electrical properties in the vicinity of the borehole. A particularly beneficial feature of single-hole radar is its capability to also image reflections from discontinuities that are inclined with regard to the borehole trace. Depending on the electrical ground resistivities (electrically conductive features attenuate electromagnetic waves) reflectors can be imaged at several tens of metres away from the borehole [230] (in dry salt up to some hundreds of metres).

  The methodology is well known from being applied in hard rock environments to locate fracture systems e.g. in the Swedish radioactive waste management programme. However, a trial borehole radar survey was undertaken by Nirex in 1993 using the Swedish RAMAC system, which is also used by SKB, with antennae having 22 MHz and 60 MHz centre frequencies. The trial showed that the investigation distance was limited to 5 to 10 m from the borehole under the site-specific conditions. The results showed that the technique was limited to zones of low-resistivity rock mass and in those areas of low electrical-conductivity formation fluids. At that time (1993) maximum investigation distances seen from the mining/quarrying industries suggested that borehole radar could provide information to distances of the order of 60 m from the borehole. This investigation distance was attained in a limestone rock mass that contained few shale or clay layers/beds.

  Subsequently, SKB [223] has identified a need to replace the RAMAC borehole radar system with a new equivalent system prior to the commencement of site investigations at potential spent fuel repository sites, and a new borehole radar system with 20 MHz, 100 MHz, and 250 MHz dipole antennas has been developed [223]. Recently, Serzu et al. [224] have reported that use of the RAMAC system operating at 60 MHz provided high-resolution reflection records and detected reflectors up to 50 m away from the boreholes at the URL site in Canada. Compared to 60 MHz surveys, the 22 MHz reflection data showed marked decrease in resolution but considerable increase in probing-range (~100 m). Both the 22 and 60 MHz surveys were able to detect water-saturated discrete fractures and fracture zones a few centimeters thick.

- *Single-hole seismics*
  The principle of single hole seismic is similar to single-hole georadar, but instead of electromagnetic waves the method employs high-frequency elastic waves. Typical seismic sources are sparkers, borehole hammers or piezoelectric devices. The seismic waves are recorded with geophones or hydrophones.

The far-field methods have the potential of characterising anomalous features at quite some distances away from a borehole, but all of them suffer from an inherent limitation. The azimuthal symmetry of the experimental setups usually does not allow the absolute location of the anomalous features to be determined unambiguously. Nevertheless, these techniques could be a useful option for repository monitoring, where only temporal changes are of interest. It is unlikely that single-hole far-field methods are capable of capturing changes within the seals of a repository, but they could be useful for detecting possible leaks at the buffer - host rock interface.

3.2.2.2 Cross-hole methods

Using two or several boreholes that encompass a repository, detailed information about its actual state of its interior and its surroundings can be obtained. In principle, any geophysical method that involves an active source can be applied in cross-hole mode. Cross-hole techniques can be employed for imaging and monitoring purposes and are currently viewed as the most promising approach for non-intrusive monitoring of radioactive waste repositories.

Seismic methods
Standard seismic cross-hole analyses include travel time and amplitude tomography [221]. These techniques allow complete features (and temporal variations thereof) to be imaged. During recent years, seismic waveform inversions experienced an enormous gain in popularity, e.g. [227]. Compared with travel time and amplitude tomography they have a much better spatial resolution, and they have the potential to monitor even subtle changes within a repository. However, there are still a number of technical and methodological issues (e.g. distance of the borehole in relation to the monitored object, reproducibility of the data) to be resolved, before this method can be applied on a routine basis [228].

Georadar methods
Georadar methods can be applied in a similar way to seismic cross-hole tomography. Conceptually, georadar would be therefore also suitable for monitoring radioactive waste repositories, but high-frequency electromagnetic waves hardly penetrate through clay-based materials limiting its application in clay materials. Since clay is a potential host rock for many countries and/or bentonite may be employed as a buffer surrounding the waste material, it is generally not expected that georadar will play a major role in near-field repository monitoring.

Electric and electromagnetic methods
The low to intermediate frequencies employed in electromagnetic surveys (from a few kHz to a few hundreds of kHz) work particularly well in electrically conductive regions [244]. This makes them potentially attractive for monitoring radioactive waste repositories. Downsides of this technique include (i) the limited availability of suitable equipment, and (ii) the diffusive nature of the inductive electromagnetic processes, which results in a reduced spatial resolution power.

Therefore, electromagnetic methods are expected to be useful only in combination with other techniques, such as seismics.

3.2.2.3 Surface-to-borehole and borehole-to-surface methods

In contrast to the single-hole methods, described in section 3.2.2.1, these types of geophysical techniques involve surface-based sources or receivers. These geophysical techniques are therefore capable of imaging the area between the surface and the maximum depth of the borehole and to a certain extent looking ahead the well bottom. Consequently, they are useful for characterising gross structures between a repository and the surface, but they are not expected to provide detailed information about changes within a repository. Surface-to-borehole and borehole-to-surface methods are suitable for both imaging and monitoring purposes.

Seismic, electric and electromagnetic methods are applicable in surface-to-borehole and borehole-to-surface configurations. As georadar usually has a very limited exploration depth and "mise à la masse" techniques requires special conditions for source coupling [226], only seismic methods are relevant to repository problems.

Seismic methods
Vertical Seismic Profiling (VSP) is a class of seismic measurements that can obtain high resolution images near the wellbore [225]. VSP is a generic term covering a range of seismic surveys that employ a seismic source deployed on the surface and a downhole receiver string that records the transmitted and reflected seismic energy. This allows essentially 1D (one-dimensional) subsurface information to be extracted. Typically, reflections from horizontal or sub-horizontal discontinuities are analysed. This is achieved by a wavefield separation into upgoing (reflected) and downgoing (direct) fields [198]. Besides imaging the geometry of horizontal or sub-horizontal reflectors, depth interval velocities can be obtained from analyses of the direct waves.

The methodology can be considered to bridge the gap between investigations undertaken in the borehole with those based on the surface such as surface seismic surveys. The technique was initially developed for correlating borehole-derived information with that obtained from surface seismic surveys, and also to check the velocity of propagation of seismic energy through the rock mass.

In recent years multi-offset VSP surveys have been undertaken [242], [243], which allow limited 2D information to be obtained, and are now being recorded also in a 3D sense [241]. Acquiring VSP data in a 3D sense removes out-of-plane effects and errors, is able to consider azimuthal anisotropy, and allows for a better horizontal and vertical resolution than that obtained from surface 3D seismic data. These data sets can be integrated with surface seismic data to provide high-resolution structural imaging and time-depth correlation, as well as the ability to link seismic attribute maps to petrophysical information such as porosity.

Among other seismic attributes, Amplitude Variation with Offset (AVO) analyses, derived from time-lapse surface 3D seismic data, can be used to provide information on fluid movement in the sub-surface. In comparison to VSP data the seismic waves recorded on the surface have travelled twice through the rock mass and consequently have reduced amplitudes and are more affected by scattering and attenuation as well as these data is stronger subject to variations due to heterogeneity of the overlying materials. The resulting uncertainties which could affect surface seismic AVO analysis can be reduced by carrying out AVO analysis of VSP data, which can then be used to calibrate the surface seismic AVO data. Additionally, with a properly designed VSP survey, wider reflection angle apertures can be acquired than with surface seismic geometry, providing additional information.

The next step in VSP methodology is to apply 3D VSP surveys in a time-lapse manner. Such developments are underway.

3.2.3 Groundwater and Chemistry

Groundwater pressure

Groundwater pressures and other parameters can be measured directly using downhole wireline probes. Multi-level piezometers can be installed in shallow boreholes. In deep boreholes (typically from a few hundred to a few thousand metres), a multi-packer system can be used to isolate specific sections of the borehole, and pressures can be measured using piezometers or transducers. Posiva combines the measurement of resistivity, electrical conductivity, and temperature in combination with its detailed flow logging using the difference flowmeter [229].

Measurements can be taken periodically or continuously. The Diver family of data loggers (VanEssen Instrument) is based on a sealed, stainless steel housing that contains internal memory, an internal battery (8-10 year lifetime) and sensors. They provide continuous low-maintenance measurements of dissolved oxygen concentration (range 0 – 20 mg/l, resolution 0.01 mg/l), pressure (resolution of 2 cm expressed in terms of centimetres of water column), temperature (-20 to 80°C, resolution 0.01°C), and electrical conductivity. Alternatively, single-probe profiling with a MOSDAX® pressure probe (Westbay Instruments; resolution 0.008 psi) or sampler probe can be used for periodic manual measurement of fluid pressures. With a single probe, pressures are measured one port at a time, usually beginning with the lowermost port in the well and proceeding toward the top. Since the probe is not permanently installed in the well, it may be calibrated and maintained at any time. The probes can be used to measure fluid pressures both in high-permeability and very low-permeability materials.

The number of probes in a borehole is generally limited by the number of ducts that can be made through the packers higher in the borehole without weakening the packer structure. Posiva and SKB generally limit their completion to a total of seven or eight packer intervals ([230];[231]). A network of groundwater pressure monitoring systems was established in the deep Nirex Sellafield boreholes (the Long-Term Monitoring System – LTMS; [232]). The LTMS used 20 of the Nirex boreholes purpose-drilled for site investigations, and 2 recovered pre-existing boreholes. A Westbay multi-packer monitoring system was installed in each of the 22 boreholes. Monitoring probes were deployed down to depths of 1,500 m in up to 30 hydraulically isolated intervals within each borehole (The Nirex boreholes were of a larger diameter than the boreholes used in Sweden and Finland, and could therefore accommodate more probes). The probes continuously record natural variations in groundwater pressures and temperatures. The data are stored prior to being periodically down-loaded, either via telemetry to a central station or manually at the borehole.

The low hydraulic conductivity in argillaceous media creates a particular challenge for hydrogeological monitoring in boreholes, as accurate measurements require a high level of hydraulic isolation for the borehole instruments and measured section, and the volumes of open space in the borehole need to be very small to avoid extremely long equilibration times. In France, ANDRA has applied two technologies to meet this challenge [233]. The first is the use of Westbay multi-packer piezometers which isolate discrete intervals of the borehole. Electronic probes access the borehole fluids from inside the piezometer casing through pressure ports that minimise the fluid exchange from the borehole volume. This technology has been in use for over twenty years. The second technology, which is more recent, is an electronic pressure gauge, which uses low-frequency transmitters for the wireless transmission of signals. By eliminating the need for wires, the gauge can be isolated in the borehole using low-permeability cements with a minimal volume of water surrounding the instrument. The gauges have been adapted from the petroleum industry to optimise battery life and to prolong the period of measurement. At present, the instruments have been designed to have a five-year life before expending the power sources. Two gauges have been installed in Callovo-Oxfordian clay. The first began operation in 1996 and ended its transmission in 2002. The second was installed in 2001 and is currently transmitting data. Each was installed at the bottom of a borehole that contains a Westbay piezometer in the overlying portions of the borehole.

De Cannière et al. [234] describe the installation of piezometers in short boreholes into the Boom Clay at the Mol underground laboratory. In this case, water flow will be enhanced by the presence of the underground opening. Even so, times in excess of years were necessary for equilibration. The piezometers had to be constructed out of stainless steel, rather than plastics or ceramics, to withstand the in situ stresses created by natural creep of the clay.

Hydraulic Testing

Hydraulic testing in boreholes is usually carried out during drilling or immediately after completion. However, if required, all normal hydraulic tests (rising-head, falling-head, constant-head, tracer tests) can be carried out at any time after completion in packed-off zones where pumping ports are installed. However, testing can significantly disturb conditions for groundwater sampling. Therefore, testing in wells used for chemical monitoring should only be undertaken with due caution for subsequent sampling programmes.

A common hydraulic test that might be conducted in multi-packered boreholes is the constant head injection test to measure hydraulic conductivity of a section isolated between two packers [230]. Water is injected under constant pressure into the section. Absolute pressure is measured using a downhole pressure transducer above the upper packer and below the lower packer. A probe measures the pressure difference between the upper packer and the measured section. This method has been used to measure low hydraulic conductivities in sections of rock down to 2 m, where flows are below the limit of detection of the difference flowmeter.

Flow Logging

Direct measurement of flow using probes in a multiple borehole system can be achieved using chemical or radioactive tracers, thermal or mechanical flowmeters, and, less commonly, acoustic, electromagnetic, and thermal decay flowmeters.

- Mechanical or impeller flowmeters: these meters incorporate a lightweight bladed impeller that rotates as water flows past, turning a magnet that generates a pulse on a microswitch. The pulses are recorded to give a measurement of the flow velocity of the water along the borehole (i.e., vertically). During drilling, a flowmeter may be drawn up the borehole to give a continuous log. Thereafter, flowmeters can be installed at particular depths. The main problem with mechanical flowmeters is the lack of sensitivity to low flows. The addition of a flange to divert flow through the meter can improve sensitivity. A flowmeter used at Äspö had a measuring range of 2.2 to 103 litres/minute, with a resolution of 0.5 litres/minute (equivalent to flow velocities of 0.015 to >0.7 m/s, with a resolution of 0.003 m/s; [235]).

- Tracer dilution. This involves introducing a tracer into an isolated borehole section, and using a probe to measure its dilution as a function of time. The dilution is proportional to the water exchange rate and, therefore, the groundwater flow in the section. This technique can be used to detect much lower flow rates than the impeller flowmeter, down to 10-5 litres/minute. However, problems are the difficulty of interpreting results, and potential chemical contamination.

- Acoustic flowmeters. A flowmeter has been developed by SKB that uses the travel time of acoustic waves to determine the magnitude and direction of groundwater flow along a borehole based on the Doppler effect [235]. The measuring range and resolution of the meter are 0.15 to 450 litres/minute, with a resolution of 0.15 litres/minute (equivalent to velocities of 0.001 to 3 m/s and 0.001 m/s, respectively).

- Electromagnetic flowmeters. In electromagnetic flowmeters, an electromagnet creates a magnetic field in the flow tube of a probe and the water flow then creates a voltage gradient that is proportional to the flow velocity. The gradient is measured by two electrodes [236]. Although not widely used, electromagnetic flowmeters have a lower detection limit and resolution similar to the acoustic meters, and they have no practical upper flow limit.

- Thermal flowmeters. These meters are based on either a thermal pulse being used to heat water, the flow of which is monitored using extremely sensitive thermal sensors, or thermal dilution, whereby the cooling speed of the heating thermistor is measured (faster cooling means faster flow). The former tends to be used for slower flow rates. Two types of thermal flowmeter have been developed by Posiva, specifically to address issues such as low flow rates, wide flow ranges, flexibility, and fast performance ([237]; [229]):

  - Difference flowmeter. This meter is used in two modes: normal mode, using both thermal pulse and thermal dilution methods for low and high flow rates, respectively; and detailed mode using the thermal dilution method only. The measuring range is 1E-04 to 5 litres/minute. The difference flowmeter is moved up the borehole, giving a continuous flow log from which single flowing features (fractures) can be detected. The two modes differ in the rate / steps at which the meter is moved.

  - Transverse flowmeter. This meter can be used to measure flow across boreholes. Potentially interesting sections for further investigation are identified using the log produced by the difference flowmeter. A 2 m section is isolated using packers, and the section is divided into four sections using longitudinal inflatable seals that guide flow through the flow sensors. Thermal pulses are used to detect flow and flow directions with a sensitivity of 10^{-4} litres/minute (equivalent to velocities of 2 x 10-9 m/s).

- Dual burst thermal decay time logs: Dual burst thermal decay time logs are used in the oil and gas industry. These tools introduce bursts of fast neutrons in the downhole environment, the decay of which can be analysed using a diffusion model to monitor fluid flow. This approach is useful in time-lapse logging where fluids in the borehole change through time.

Results from flowmeters are used to identify flowing zones and flow directions, and to determine hydraulic conductivities and hydraulic heads.

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3.3 Surface-based monitoring

Surface-based site characterisation techniques are routinely applied to support the characterisation of geological structures (e.g. for the exploration of future repository sites), and to locate natural resources, such as coal, oil and gas and mineral deposits. Seismic reflection surveys (Section 3.3.1) were a significant component of such exploration work. In addition, during the 1990s industry’s emphasis was extended to the efficient production of known reserves. This required more detailed characterisation of the sub-surface and development of techniques to understand the dynamic behaviour of the geosphere during production (e.g.

movement of hydrocarbons during oil and gas production, and dynamic effects related to mining). One of the most significant advancements has been the development of 4D seismic reflection surveys (Section 3.3.1) and, therefore, this technique is discussed in more depth than other techniques considered in this section.

Seismic techniques generally involve measuring the travel time of certain types of seismic energy from surficial shots (i.e. an explosion or weight drop) through the subsurface to arrays of ground motion sensors or geophones. In the subsurface, seismic energy travels in waves that spread out as hemispherical wavefronts (i.e. the three dimensional version of the ring of ripples from a pebble dropped into a pond). The energy arriving at a geophone is described as having traveled a ray path perpendicular to the wavefront (i.e. a line drawn from the spot where the pebble was dropped to a point on the ripple). In the subsurface, seismic energy is refracted (i.e. bent) and/or reflected at interfaces between materials with different seismic velocities (i.e. different densities). The refraction and reflection of seismic energy at density contrasts follows exactly the same laws that govern the refraction and reflection of light through prisms. Note that for each seismic ray that strikes a density contrast a portion of the energy is refracted into the underlying layer, and the remainder is reflected at the angle of incidence. The reflection and refraction of seismic energy at each subsurface density contrast, and the generation of surface waves (or ground roll), and the sound (i.e. the air coupled wave or air blast) at the ground surface all combine to produce a long and complicated sequence of ground motion at geophones near a shot point. The ground motion produced by a shot is typically recorded as a wiggle trace for each geophone (see Example Seismic Record at right)

3.3.1 **Seismic Reflection Surveys**

Seismic reflection uses field equipment similar to seismic refraction (see 3.3.2), but field and data processing procedures are employed to maximize the energy reflected along near vertical ray paths by subsurface density contrasts (see Seismic Refraction Geometry below). Reflected seismic energy is never a first arrival, and therefore must be identified in a generally complex set of overlapping seismic arrivals - generally by collecting and filtering multifold or highly redundant data from numerous shot points per geophone placement. Therefore, the field and processing time for a given lineal footage of seismic reflection survey are much greater than for seismic refraction. However, seismic reflection can be performed in the presence of low velocity zones or velocity inversions, generally has lateral resolution vastly superior to seismic refraction, and can delineate very deep density contrasts with much less shot energy and shorter line lengths than would be required for a comparable refraction survey depth.

Seismic reflection surveys are undertaken in either 2D or 3D modes. 3D surveys may be repeated over time, in which case they are referred to as 4D (also: time-lapse 3D) seismic surveys. The development of seismic reflection surveys commenced with 2D surveys. In 2D seismic surveys, receivers (geophones on land or hydrophones in the marine environment) are used to form a linear array, and the seismic energy source is placed in line with the receivers. The energy from the seismic source propagates through the sub-surface, is reflected at velocity boundaries and recorded by the geophones or hydrophones.

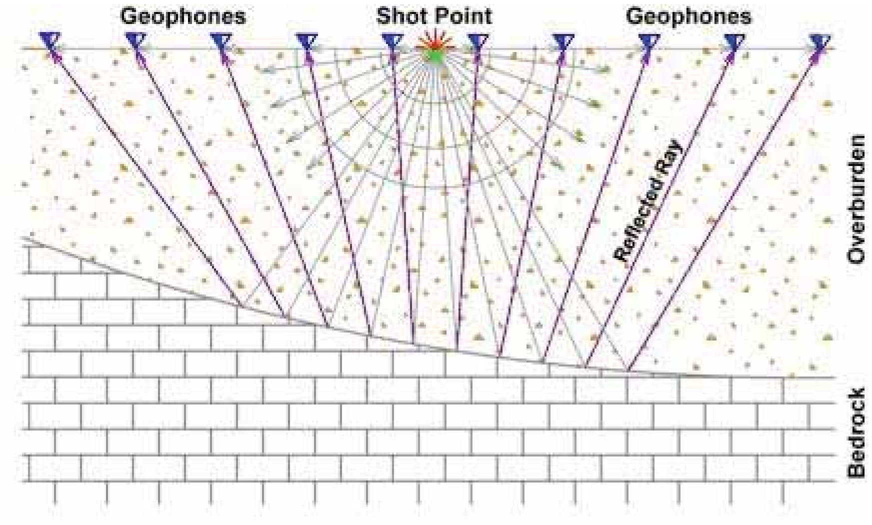

Figure 95: Seismic refraction geometry (source Enviroscan Inc.)

With the evolution of more sophisticated signal handling and processing capabilities, the methodology applied in 2D seismic surveys has been expanded to form 3D seismic surveys. In such surveys, the seismic receivers are placed to cover a large area in the form of a grid, and usually the energy source is used either parallel (in marine surveys) to the lines of receivers or perpendicular to them (in land surveys). The main difference between 2D and 3D methods is the ability to reconstruct an image of the subsurface in 2D or 3D. 2D data can only position reflections in the plane beneath the survey line, and basically neglect the out-of-plane effects. 3D processing attempts to place the reflected energy at the correct 3D spatial location.

3D technology is most commonly applied in the oil and gas industry. Some examples are also available from the mining industry; however, 3D seismic reflection surveying is not generally used for monitoring purposes in the mining industry. This review concentrates on the application of seismic reflection surveys applied to monitor fluid movement, as this is potentially the most likely scenario for post-closure monitoring.

In February 2003 the European Association of Geoscientists and Engineers published an issue of Petroleum Geoscience that contained 12 papers covering 4D seismic technology. One of the most pertinent papers is an overview of 4D technology authored by de Waal and Calvert from Shell [245].

Shell utilises 4D technology as an integral component of oil and gas field management and are looking at extending the conditions by which the technology may be applied. De Waal and Calvert [245] recognise three general means by which this may be achieved:

1. **Extension of Proven Technology:** It is anticipated that 4D seismic surveys may be more widely applied to the monitoring of fluid movements in thick sandstone sequences in marine environments. This is the current standard application of 4D technology. Results of repeated surveys are compared with the output from reservoir simulators in order to refine the approach to production of oil.
2. **Stretch:** The second possibility is termed “stretch” by de Waal and Calvert [245]. This refers to the extension of 4D technology to other scenarios including gas reservoirs and land-based surveying.
3. **Incorporation of New Technologies:** The third possibility being considered is the application of future technologies, for example permanently deployed arrays, downhole

acquisition, passive monitoring (e.g. acoustic emissions, see Section 3.3.7), and smart fields where semi-continuous 4D monitoring is undertaken.

The monitoring of a hydrocarbon reservoir covers a range of scientific-based studies and financial evaluations, with time-lapse 3D being one component of a larger strategy. This is shown by de Waal and Calvert (2003) in their "4D Value Loop" (Figure 96). The 4D Value Loop indicates that 4D seismic surveys are only one aspect of integrated monitoring programmes, and that a number of other disciplines and methodologies are required as part of the overall scheme.

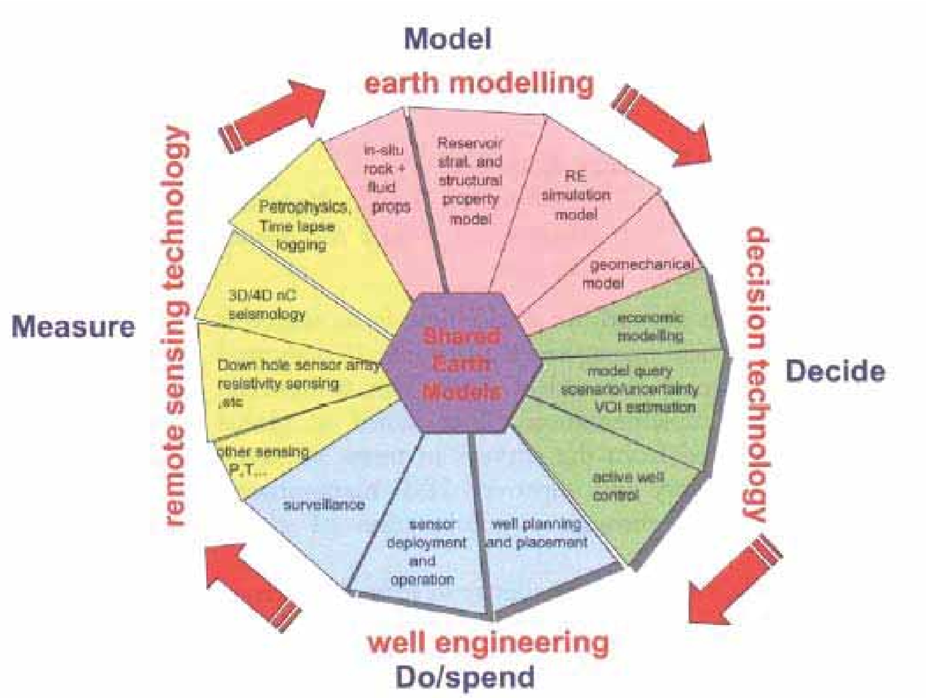

Figure 96: The 4D Value Loop after de Waal and Calvert [245]. This indicates that the seismic survey is one small component of an overall strategy

Feasibility studies are required prior to undertaking a 4D seismic survey. This would involve the study of rock and fluid properties, analysis of existing 3D seismic data and confirming the repeatability of 3D surveys. This phase of work includes prediction of the anticipated sub-surface changes, and modelling of the anticipated seismic response, with the objective of determining whether predicted changes could be detected, and to determine the optimal time and set-up for the acquisition of the 4D survey. This suggests that the technology is not necessarily appropriate to all geological environments, as a time dependent response may not be measurable in all cases. However, the effectiveness of this technique could be characterised during the site investigation phase.

De Waal and Calvert [245] report that "hard reservoirs" often yield small 4D signals. The term "hard reservoirs" is generally applied to limestone reservoirs in the oil and gas industry, rock types of an igneous origin are not commonly considered, as they rarely contain hydrocarbon reserves. The ability to detect smaller 4D signals from "hard reservoirs" is one of the issues that Marsh et al. [246] discuss; they consider that this is one of the areas requiring improvements in seismic quality.

The purpose of the 4D surveys is generally to monitor the progress of procedures to enhance hydrocarbon recovery, including water-flood and steam-flood methods. These methods involve the injection of water or steam in order to drive hydrocarbons towards producing wells. The 4D surveys are undertaken to monitor/locate the position of fluid contacts such as the gas/water contact.

Figure 97 illustrates the results from a pilot 4D survey overlain by a reservoir model, which illustrates water encroachment [245]. This situation may possibly be considered in an inverse sense, i.e. resaturation of a rock volume and generation and migration of a gas phase may be generated and could migrate.

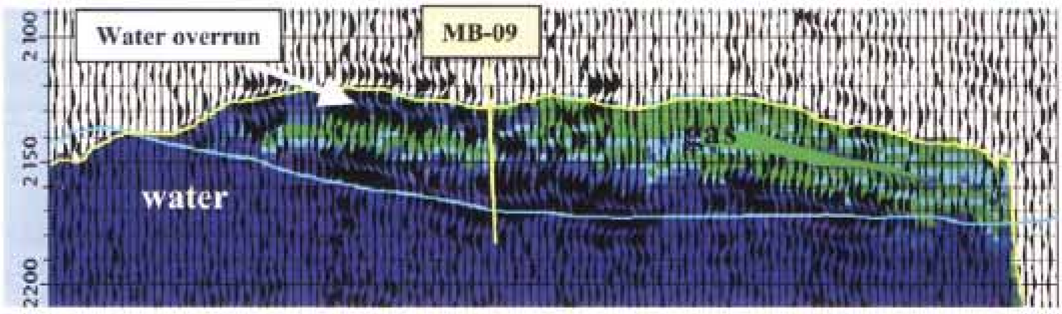

Figure 97: The results of a pilot 4D seismic survey overlain on a reservoir model [245]

4D seismic surveys can also be used for reservoir management [247]. For example, in gas reservoirs, the acoustic impedance could significantly change during production, because the gas pressure is decreased and the gas is replaced by other fluids (water or oil).

Several papers discuss the use of acoustic impedance volumes or difference sections to monitor fluid movement. Marsh et al. [246] discuss the use of AVO analysis and the selection of the optimal impedance volume to image fluid contacts. This interface was calibrated with appraisal wells (analogous to investigation boreholes drilled to investigate a rock volume). The positive correlation of the seismic image of the fluid contact movement with that shown by production logging tools supports the use of 4D seismic surveys to monitor fluid movement [246].

Kloosterman et al. [248] also report the use of amplitude changes and acoustic impedance to monitor fluid movement from the Central North Sea. Differences in the acoustic impedance volumes between 3D surveys were used to interpret changes in fluid movement in the reservoir, specifically the oil-water contact (OWC), and changes in pressure/temperature conditions. There are also drawbacks to the use of time-lapse 3D seismic surveys as in some parts of the studied field there was no time dependent response. It was considered that this may have been due to a lack of seismic resolution. Resolution of geological structures is dependent on seismic velocity of the rocks and the frequency content of the seismic signal in the considered depth. Kovacic and Poggiagliomi [249] report resolutions of about 9 m in their study on a gas field in the Adriatic.

The integration of seismic data with other data is important for interpretation. For example, Najjar et al. [250] discuss the work undertaken for a field in the Norwegian section of the North Sea. Prior to undertaking the baseline 3D survey, a feasibility study was carried out in order to evaluate how the seismic response from the reservoir may change with varying fluid concentrations. The study involved the construction of a rock physics model that was based on wireline data and ultrasonic core measurements. Forward modelling was used to generate time-lapse synthetic amplitude and acoustic impedance volumes. The work suggested that the fluid pressure has a little effect on the Vp/Vs ratio, although saturation (fluid content or change in content) has a significant effect. Hence, AVO analysis may be a method of separating pressure from saturation changes. The integrated workflow reported by Najjar et al. [250] incorporated the use of a 4D earth model, core data and well data to link the seismic response to predictions of flow based on a reservoir simulation. This approach was used to improve the understanding of the 4D anomalies in terms of fluid movement.

A similar workflow was reported by Kovacic and Poggiagliomi [249], where measurements and analysis of core samples were undertaken to develop a petro-acoustic model that could be calibrated against a seismic acoustic impedance volume to produce reservoir description parameters. This enabled visualisation of fluid movement in the main reservoir and led to the identification of areas where the gas may have been only partly depleted. Kovacic and Poggiagliomi [249] identify a number of fundamental issues that are related to seismic repeatability, amplitude fidelity, resolution and petro-acoustic relationships. One important point raised was that the base surveys and subsequent surveys may be acquired with different goals and may therefore have different acquisition parameters. This should be considered at the planning stages of the site investigation (base survey). Kovacic and Poggiagliomi [249] consider that a feasibility study should be undertaken to determine whether acoustic changes related to fluid movement are of a sufficient magnitude to be detected seismically.

Santos et al. [251] also report a multi-disciplinary technical approach, including the integration of geological and seismic modelling, petrophysical simulations, seismic processing and interpretation as well as reservoir simulation. Both 3D geological and 3D seismic modelling tools are required to support interpretation and 4D interpretative processing. Both Santos et al. [251] and Hubans et al. [253] compare seismic amplitude difference maps, which are related to fluid movement, with flow simulations from reservoir simulation models. Santos et al. [251] also report that the wells were completed with temperature and pressure gauges. Water injected to assist production was marked with tracers to assist in the interpretation of flow paths. The main problem of tracer injection was the large differences in distances between the wells and the degradation/dilution of the chemical tracers due to dispersion.

Elastic inversion techniques applied to time-lapse 3D AVO datasets can be used to convert reflectivity data to acoustic impedance, shear impedance and Poisson’s ratio [252]. Optimised imaging was achieved through a combination of seismic modelling, detailed petrophysical analysis of well log and core data and elastic inversion of the 4D seismic data. Inverting sub-sets (sub-stacks) for AVO analysis (offset or angle stack seismic data) has three main advantages over conventional AVO analysis:

- the inversion removes wavelet effects,
- the inversion suppresses random noise, and
- the inversion improves bandwidth.

Full elastic inversion has the advantage that it does not contain residual tuning phenomena and is better at attenuating random noise. Residual tuning is being understood as a phenomenon of constructive or destructive interference of waves from closely spaced events or reflections. Using the outputs from far offset data shows the fluid properties but these are insensitive to pressure effects. The elastic inversion data sets are used to quantify the change in the location of the oil/water contact and these changes are verified by comparison with repeated production logs.

A further complicating factor to monitoring fluid movement using seismic reflection technology is where a rock volume (reservoir) is compacting and subsiding. Nickel et al. [254] discuss compacting reservoirs and the need to separate compaction and fluid effects as both factors are time variant. In such cases the application of passive seismic monitoring (Acoustic Emission/Microseismic Monitoring, see Section 3.3.7) technology can be incorporated to delineate active fault/fracture systems. One of the main factors in being able to separate compaction and fluid effects from seismic data is ensuring repeatability. This is best achieved where sources and receivers are as close as possible to the same positions for all surveys, and acquisition is undertaken in the same direction for all surveys. On land this is relatively straightforward as positions can be surveyed or sensors left in place.

In summary a number of threads or themes are seen in these case histories:

- feasibility studies are usually required,
- 3D earth models should be generated,
- generation of synthetic data sets,
- integration of seismic data and borehole derived data,
- flow modelling or reservoir modelling should be undertaken,
- convergent processing of data sets of different vintages,
- repeatability of surveys is an issue,
- correlation and verification of seismic interpretations with repeated wireline borehole logging, and
- the first (base) survey should be undertaken with a view to the goals of future monitoring surveys.

The components of a time-lapse 3D seismic monitoring system are well summarised in Figure 96, which illustrates The 4D Value Loop [245]. In Figure 96, the authors indicate that integration of a range of earth science disciplines is of importance for a successful monitoring system to be established.

For 4D technology to be effective, de Waal and Calvert [245] suggest that there are a number of technical and organisational factors that need to be embraced. Technical factors include:

- the availability of an initial base data set,
- repetition of the base survey acquisition geometry, and
- joint reprocessing of the base and repeat surveys.

The organisational factors include:

- changing the perception of 4D technology from a cost to a value,
- management support and involvement at all levels,
- involvement of the stakeholders in project definition, planning and start up, and
- regular effective communication with all stakeholders.

The case studies briefly reviewed here show that this methodology can be used to monitor fluid movements in the deep subsurface (depths of several thousand metres) of porous and permeable hydrocarbon reservoirs. Moreover, it can be stated that 4D seismic has evolved during the past decades to a practical reservoir monitoring tool, including the monitoring of CO_2 sequestration [255], [256], [258], although examples of 4D seismic reservoir characterization in tight reservoirs are quite rare [257]. The successful application depends mainly on the repeatability of a seismic survey and the detectability of changes in the elastic properties of the reservoir. In this context it must be considered that the changes of fluid saturation, phase, pressure, or temperature in a very porous relatively soft rock result into a much larger amount of change in elastic properties than in a low porous hard rock. If this might restrict the application of 4D seismic for the conditions of a repository site must be clarified in feasibility studies considering the specific rock physics site conditions.

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3.3.2 Seismic Refraction Surveys

Seismic refraction involves measuring the travel time of the component of seismic energy which travels down to the top of rock (or other distinct density contrast), is refracted along the top of rock, and returns to the surface as a head wave along a wave front similar to the bow wake of a ship (see Seismic Refraction Geometry below). The shock waves which return from the top of rock are refracted waves, and for geophones at a distance from the shot point, always represent the first arrival of seismic energy.

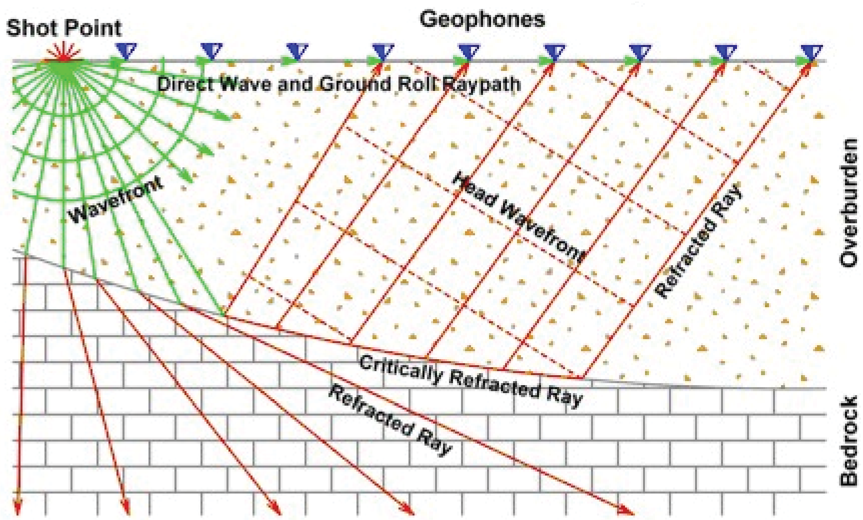

Figure 98: Seismic refraction geometry (source Enviroscan Inc.)

Seismic refraction surveys can generally be considered under two classes:

1. Deep structural investigations of the subsurface.
2. Shallow high-resolution investigations.

The deep structural studies usually involve investigations of the lower crust of the earth where the objective of the surveys is to provide information on the lithosphere. Shallow seismic refraction surveys are more generally undertaken for engineering studies with exploration depths in the decametre range. The result of a seismic refraction survey provides a velocity field in the depth domain. As velocity is directly related to elastic properties of the materials illuminated by the seismic waves, this method can be used to monitor changes of elastic properties. Like seismic reflection surveys the successful application of this method depends mainly on the repeatability and the detectability, which should be evaluated in a feasibility study before the survey considering the specific site conditions.

An example for a shallow seismic refraction survey determining the depth to bedrock beneath a proposed dam is shown in Figure 99, where the velocity field up to a depth of 60 metres interpreted as alluvium and colluvium overlying bedrock is illustrated. The data from the survey were processed using a state-of-the-art ray trace modelling technique with a tomographic travel time inversion.

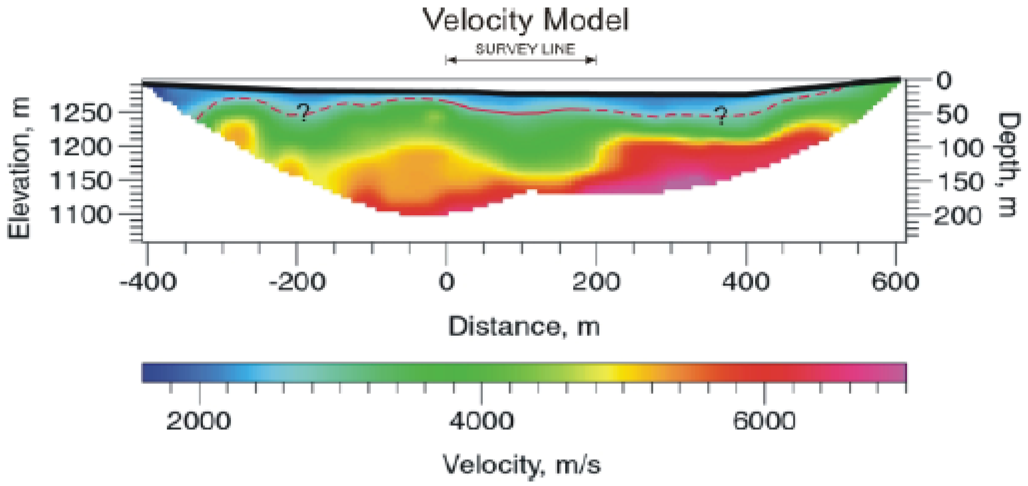

Figure 99: Results of a seismic refraction survey to determine depth to bedrock at the site of a proposed dam.

3.3.3 Gravity Surveys

Gravity surveys are applied in a large range of situations, from deep structural investigations of the structure of the earth's crust and lithosphere to shallow high resolution investigations.

Micro-gravity techniques are a particular type of gravity measurement in which the interpretation of changes in the sub-surface density distribution are made from measurement of tiny variations in the gravitational attraction of the Earth. Micro-gravity can be used for monitoring fluid movement, and research into the monitoring of time-varying (4D) gravity fields related to hydrocarbon reservoirs is currently being undertaken (Styles, pers. comm.).

Gravity surveys and measurements have generally been used in the past in conjunction with 2D seismic reflection surveys. The data were usually acquired along the same 2D lines used for the acquisition of seismic reflection data. Better results can be achieved if the gravity surveys were done in the whole investigation area as then gravity results can additionally provide structural information between the seismic profiles. The gravity data were commonly used to verify the structural models of the subsurface created on the base of the seismic results and, in turn, they were used to help constrain the interpretation of the seismic data. This was still the case in the 1990s during the acquisition programmes undertaken by Nirex. However, this integrated approach is less frequently applied since the advent of 3D seismic surveys. In the investigations of salt domes, such a combination of 3D seismic and gravity surveys is still used in recent times.

Nonetheless, as Reid [259] discusses, gravity modelling is now being integrated with seismic processing to speed up interpretation.

Reid [259] also indicates that techniques using absolute gravity measurements (as opposed to standard surveys that use relative gravity methods) and gravity tensors are being applied for reservoir modelling and for other reservoir issues.

Micro-gravity techniques have been proven to be of value in the location of sub-surface cavities, and are generally effective up to 100 m below surface. Micro-gravity is also understood to be useful in monitoring the depletion of underground aquifers, not only for water supplies but also for geothermal reservoirs (Styles, pers. comm.). Considerable work has been conducted in the United States to determine and monitor mass redistribution due to fluid extraction and reinjection. Once the gravity field has been established for a particular aquifer, it can then be monitored over time and the data applied to hydrological models. The associated mass redistribution will cause a time-varying (4D) micro-gravity signal detectable from repeated surveys.

Research is being undertaken at Keele University into techniques for determining fluid movement and changes in physical properties during the enhanced recovery phase of an oil or gas reservoir's extraction cycle. The use of time-varying micro-gravity monitoring may allow the monitoring of petrophysical changes (such as pore fluid content) within the reservoir.

Changes due to fracturing, and changes in pore-fluid composition due to compaction or to changes in pore content, cause small changes in gravity. These are superimposed upon much larger variations due to height, latitude, Earth tides and regional geological variations. However, these external changes can be modelled or monitored with sufficient accuracy to be removed from the data. With modern high-resolution equipment, careful field acquisition, and sophisticated reduction and analysis, anomalies of the order of 10 microgals can be detected and interpreted ([260]; [261]). Depending on the extension and the density contrast of the investigated object, this technique may be effective up to 300 m below surface (Styles, pers. com.). However, equipment and processing improvements may extend micro-gravity monitoring to greater depths.

The anomalies reveal the location of density variations and also provide information on the depth and shape of features causing the anomaly. The amount of material which has been added to, or lost from, the location of an anomaly (the mass changes) can be estimated by Gauss' theorem directly from the anomaly map without any prior knowledge of the exact location or nature of the targets. With some a priori knowledge from other measurements, such as formation density logs and borehole gravimetry, accurate models of subsurface density distribution can be made.

The research that is being undertaken at Keele University (Styles, pers. comm.) applies repeated micro-gravity observations at selected sites throughout a sweep phase to determine the temporal changes in mass distribution caused by the progress of the sweep through the reservoir. This has the advantage that many of the corrections necessary to isolate these small anomalies are automatically removed (latitude, terrain, height) or are being monitored (Earth Tide, piezometric) by this procedure. Preliminary forward numerical simulations show that very significant anomalies (> 350 microgals) can be generated during reservoir fluid replacement cycles. The incorporation of a priori knowledge, including the depths and position of pressure fronts, should greatly enhance the inversion of the micro-gravity data to give mass anomaly distribution maps of the fluid replacement.

In general, (micro-)gravity surveys are undertaken on land, although borehole, marine and now more commonly airborne surveys are also carried out. Sander [262] reports that results of airborne gravity surveys correlate well with ground-based surveys. In this context it must be considered that the accuracy of ground-based survey is approximately hundred times better than an airborne survey. Sander [262] also reports that an airborne gravity survey has been acquired over a major oilfield. The area had been extensively surveyed by a ground-based gravity survey acquired in conjunction with a 3D seismic survey.

Gravity surveys could be useful for repository monitoring, if the expected changes of the gravity field, which results from a density change associated to some mass transport (e.g. collapse of cavities, fluid movement) within the repository, exceed the uncertainty of the gravity measurement.

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3.3.4 **Magnetic Surveys**

Magnetic surveys can be undertaken on land, at sea or from the air. They map the variation of magnetic susceptibility, which in natural systems is most likely to be a function of the changes in the percentage of magnetite in the rock. To take these measures magnetometers are used, which measure the strength and/or direction of the magnetic field in the vicinity of the instrument. The methodology is now considered to be of high-resolution and high-sensitivity, and is capable of delineating sedimentary structure, when magnetic materials are present [263].

Magnetic survey methods are generally used either for deep crustal/regional studies or for shallow investigations. Depending on the extension, mass and the susceptibility contrast of the investigated object, shallow applications of magnetic surveys often involve the location of buried iron objects to depths of 100 m [265]. In addition, aeromagnetic surveys are undertaken for mineral prospecting in the mining industry. Since there will be significant quantities of iron present in a repository – especially in those whose concept envisages steel canisters - it is expected that a repository will be detectable as a magnetic anomaly.
An example of the capabilities of the method is provided by Stone et al. [264], who discuss the use of low-level aeromagnetic data to detect oil accumulations. The data are described by the authors as high-resolution, close line spacing, low-clearance aeromagnetic data. Although no details are provided, it is assumed that low-clearance is of the order of 100 to 200 m and that high-resolution relates to a magnetometer resolution of 0.001 nT. Using these data and careful processing techniques, the authors state that detectable magnetic aureoles can be seen in association with known fields, and suggest that magnetic aureoles may generally be indicative of hydrocarbon deposits. Stone et al. [264] consider that the aureoles arise from redox and/or bacteriological effects in response to hydrocarbon seeps.

Magnetic surveys are not further considered as a suitable application for monitoring of a repository site, because anthropogenic magnetic materials inside a repository are usually too small to detect from the surface, and on a larger scale no variation of the magnetic field is expected with any probable structural change or fluid movement related to a repository.

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3.3.5 Electromagnetic methods

Electromagnetic (EM) methods cover a wide range of equipment and techniques. Agroup of methods for determining the electrical structure of the earth using naturally existing EM fields rather than fields generated by a controlled source came into use around 1960 (Magnetoteluric methods). In the 1950s and 1960s, controlled-source frequency-domain electromagnetic (FDEM) sounding became widely used in exploration. However, interest developed in the use of EM sounding methods to explore to depths of importance for oil and gas reservoirs and for geothermal systems made necessary the transition from frequency-domain to time-domain (TD) EM methods. An additional advantage of TDEM over FDEM was the ability to sound to a great depth while the source and receiver were close together.

EM surveys map the 3D variation in electrical conductivity, caused by a number of parameters that encompass changes in mineralogy, intensity of alteration, water content or salinity, and water/fluid chemistry. This methodology also depends in part on the resistivity of the subsurface, the proximity of man-made noise sources, and the presence of metallic objects within the survey area.

EM survey methods cover a range of depths of investigation depending on the type of equipment utilised. For land-based systems, investigation depths range from approximately 1 m below the ground surface to several thousand metres below surface. Airborne EM methods are capable of achieving a maximum depth of investigation of the order of 250 m below surface (Figure 100) [270].

<u>Magnetotelluric Sounding</u> (Potential) is a natural source electromagnetic geophysical method for imaging structures below the Earth's surface by mapping the spatial variation of the Earth's resistivity using electrical currents (or telluric currents) created by natural variation in the Earth's magnetic field. The Earth's naturally varying electric and magnetic fields are measured over a wide range of frequencies (0.0001 to 10,000 Hz). Concurrent measurements of orthogonal components of the electric and magnetic fields permit the calculation of the impedance tensor, which is complex and frequency-dependent. Using this tensor, it is possible to gain insight into the resistivity structure of surrounding material [266].

The magnetotelluric sounding method was originally used for academic research. It was used successfully for the mapping of geothermal reservoirs starting in the early 1980s and became a standard application. In recent years, magnetotellurics has also become increasingly popular in oil and mineral exploration. DOE and the National Nuclear Security Administration (NNSA) at their Nevada Site Office addressed ground-water contamination resulting from historic underground nuclear testing and used magnetotelluric sounding to define the character, thickness, and lateral extent of the pre-Tertiary confining units [267].

Electromagnetic Induction Tomography (Potential) or EMIT is a promising new tool for imaging electrical conductivity variation in the Earth. Crosswell EM imaging takes advantage of the differences in the way electromagnetic fields are induced within various materials [268]. For example, rocks containing a lot of water, typically in the form of droplets bound to tiny rock pores, usually conduct electricity better than rocks containing CO_2. The technique uses magnetic fields to image the subsurface; it was developed for use by the oil and gas industry to determine where reserves are located. The electromagnetic source field is produced by induction coil (magnetic dipole) transmitters deployed at the surface or in boreholes. Vertical and horizontal component magnetic field detectors are deployed in other boreholes or on the surface. Sources and receivers are typically deployed in a configuration surrounding the region of interest. Although such electromagnetic field techniques have been developed and applied, the algorithms for inverting the magnetic field data to produce the desired images of electrical conductivity have not kept pace. EMIT is capable of mapping the changes in resistance of subsurface formations using magnetic fields.

EMIT is used to generate 3-D images of passive electromagnetic properties in the subsurface for applications such as site characterization and plume tracking. EMIT has shown success being deployed in petroleum applications for field characterization and steam flood monitoring [269]. EMIT provides greater resolution and petrophysical information than Electrical Resistance Tomography (ERT).

Time Domain Electromagnetics (TDEM) can be useful in mapping the subsurface resistivity distribution and any changes in groundwater chemistry. Figure 101 shows the modelled resistivity distribution approximately 300 m below the surface from a site in Cheshire. In the survey area, the top Halite is subject to solution and areas known as wet rock head (mobile salt in solution) and dry rock head are present. Interpretation of the results of the EM survey assume that the areas of high resistivity (red areas to the left of Figure 101) represent areas of dry rock head and low resistivities (blue areas to the right) represent wet rock head.

Whilst the example illustrated in Figure 101 is for a relatively shallow target, the methodology has the potential to be used for deeper investigations, and can be useful to show any change or movement of saline (or similar) interfaces in the subsurface

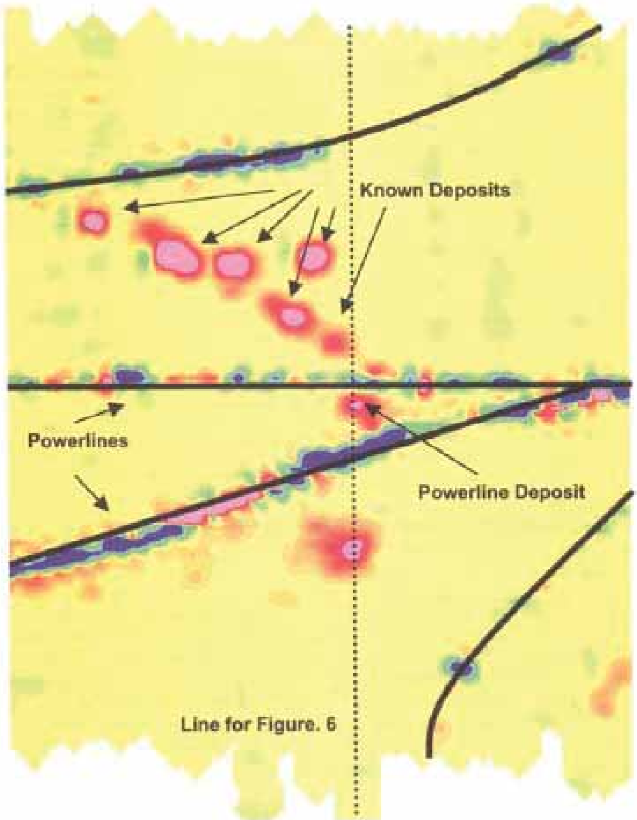

Figure 100: Plan view of the EM response measured from an AeroTEM [270]. The pink anomalies show the locations of known and newly discovered mineral deposits.

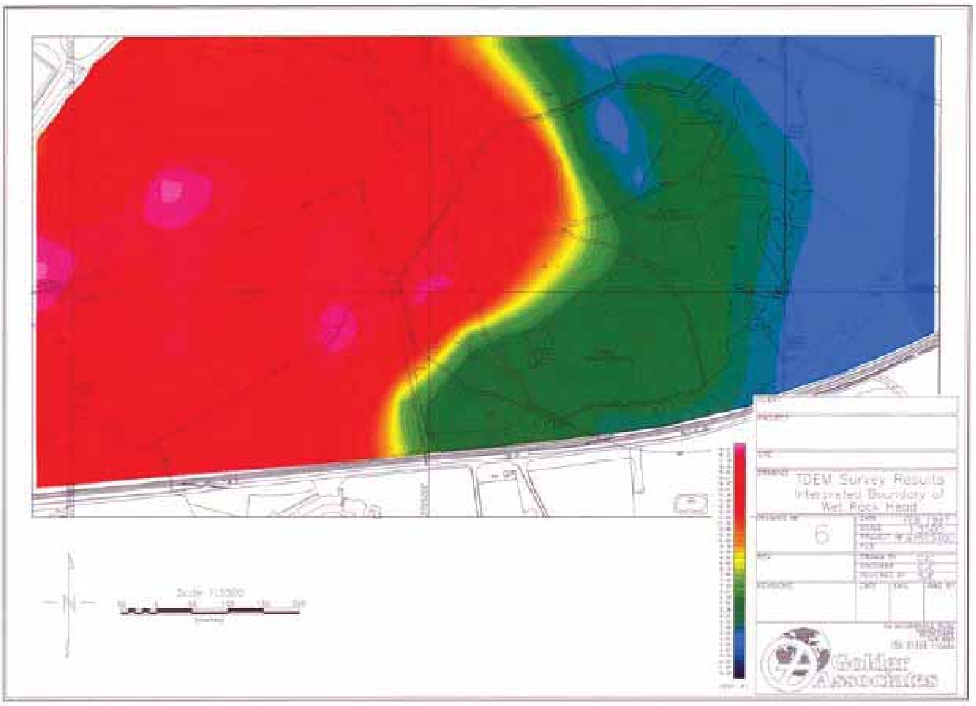

Figure 101: Modelled resistivity distribution at the interpreted top Halite.

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3.3.6 **Radiometrics**

Radiometrics is a measure of the natural or man-made radiation at the earth's surface. Radiometrics is also known as gamma-ray spectrometry. A radiometric survey measures the spatial distribution of naturally occurring radioactive elements (potassium (K), thorium (Th) and uranium (U)), or specific man-made elements present in the very near surface (0–50 cm). The abundances of K, Th and U are measured by detecting the gamma-rays produced during the natural radioactive decay of these elements. As the energy of gamma rays is related to the source radioactive element, they can be used to measure the quantities of those elements in an area. By measuring the number of gamma rays (count rate) and the energy of the gamma rays that are emitted from a certain area, the presence of particular minerals and therefore rock types can be inferred. The results of surveys are normally presented as total gamma ray activity and as equivalent ground concentrations of U, Th and K and other radionuclides, or as ratios (including ternary K, U, Th plots). However, methods have been developed to separate natural and man-made radioactivity.

The surveys are usually carried out using either land-based or airborne systems. Reconnaissance airborne surveys are usually followed up with a detailed land-based survey. Airborne gamma ray spectrometer surveys were primarily developed for uranium exploration, but have many applications in environmental monitoring and geological mapping, for example they have been used to map:

- radioactive fallout from nuclear accidents,
- contaminant plumes from nuclear power plants, waste storage sites and former military establishments, and
- the impact of uranium mining and associated waste management facilities (tailings dams).

Airborne gamma-ray spectrometry surveys are effective geological mapping tools in many different environments, including geothermal, hydrocarbon and groundwater investigations.

Gamma-ray measurements can be used as a quick and effective method of mapping large areas. Although the gamma-ray spectrometer measurements record variations in the radioactivity of a shallow surface layer of the order of 0.3 m, the results are useful for both regional and targeted surveys [271]. Systematic soil sampling and ground surveying over extensive areas can be expensive. Airborne surveys are a much faster and cheaper method for surveying over large areas, and the results can be used to identify specific areas for more detailed follow up surveys and soil sampling.

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3.3.7 **Acoustic Emission and Microseismic**

Acoustic emission (AE) or micro-seismic (MS) monitoring are generally considered to be methods for monitoring forms of induced (i.e. man-made) seismicity as opposed to naturally occurring seismicity. Naturally occurring seismicity covers a broad range of intensities, from those that are similar to induced seismicity to large-magnitude earthquakes. Seismicity results from the sudden release of accumulated strain energy that can result in a sudden movement. The frequency of the emitted seismic signals ranges from less than 1 Hz (infrasonic) to 1 MHz (ultrasonic), with the characteristic frequency of the events being dependent upon the scale of the failure occurring at the rupture surface. Frequencies of less than 100 Hz are commonly referred to as micro-seismic, while frequencies above this are termed acoustic emissions, although no objective scientific rationale exists for this division.

AE/MS monitoring is a useful method for passively monitoring an underground environment. The methodology can use sensors deployed in boreholes, underground and/or on the surface. AE/MS monitoring systems can cover a range of scales that include; regional, local and facility-wide systems. Targeted systems can also be installed to monitor specific areas of the facility, such as a particular vault(s), pillars or access shafts/tunnels. Figure 102 shows the AE data recorded during the excavation of a drift at the Äspö Hard Rock Laboratory using drill and blast methods. This has resulted in the generation of considerable numbers of AE events, but as can be seen from Figure 102, the events are located in close proximity to the excavation.

Another advantage of the AE/MS monitoring is that, once the sensors are deployed, the system works quite autonomously under consideration of necessary power supply and data transmission. This makes it also very suitable for use in remote areas or in areas with limited access.

Monitoring systems using only surface-based sensors cause a reduction in the accuracy of the resulting locations of the events, which is one uncertainty of this method. The reduction in accuracy (which can be an error of metres to tens of metres) is generally more pronounced as the depth of the AE event increases, and is caused by surface-based monitoring arrays being applied to a 3D volume. These problems can be obviated by deploying sensors both on the surface and in boreholes, providing an additional dimension to the array, which improves the behaviour of the inversion algorithm for the localisation of events. The logical extension, which could be applied in a post-closure monitoring system, is to include sensors deployed within the facility in addition to those placed on the surface and in boreholes. AE/MS data recorded at the surface are usually transmitted to a central facility using radio links, although other methods such as microwave links and cables can be used. Alternatively, data can be recorded locally to the sensor for later downloading. In the borehole and underground environment, AE/MS data are generally transmitted to the recording facilities by cable and/or fibre optic links

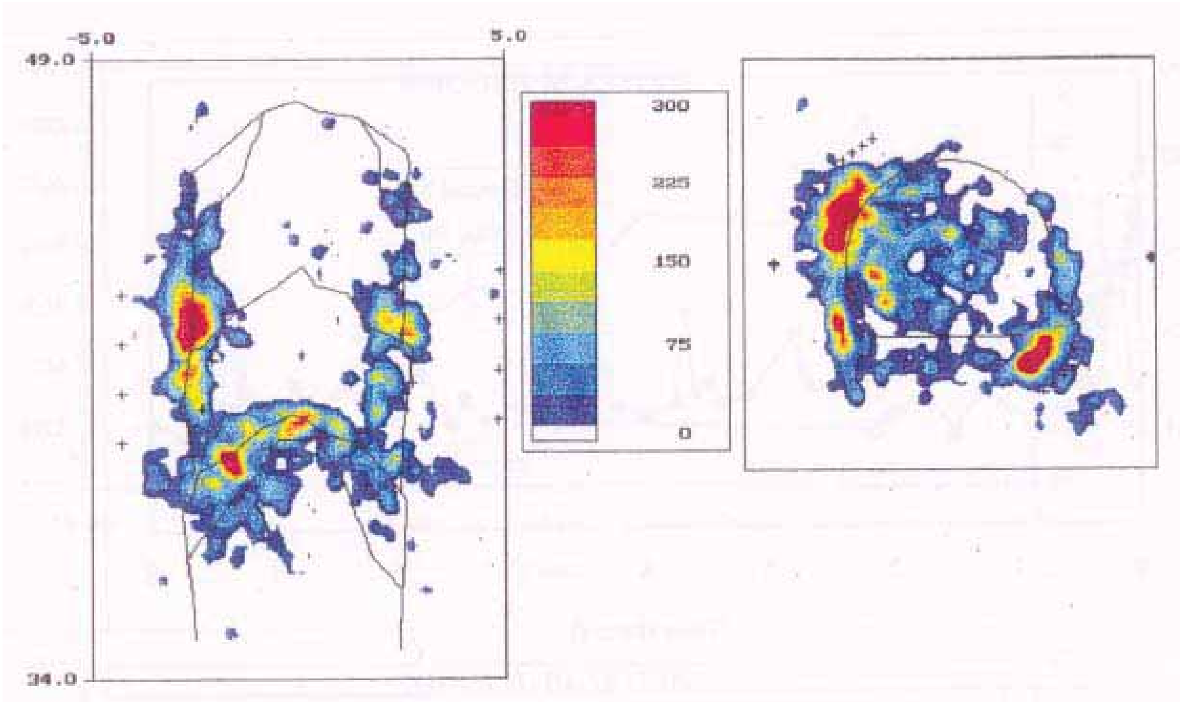

Figure 102: AE event plot contoured to show quantity of events. The left-hand image is a plan view, and the right-hand image is a sectional view of the drift and event locations. The small crosses (+) represent the transducer locations that recorded the AE events [272].

In Canada AE/MS monitoring has been used to determine the long-term stability of underground structures and micro-seismic monitoring systems have been used to characterise the stress distribution around test caverns. The data from these systems have been used to calibrate geotechnical models and to assist in the understanding of the rock response to excavation, thermal loading and the build up of pressure on the rock mass.

Microseismic surveys are regularly used to monitor hydrofracturing in commercial oil fields, as well as to track flow fronts and pressure waves during water injection. Passive seismic can be used to monitor the formations above the reservoir for evidence of migrations through the seal rock and assess fracture propagation. Prerequisite for the success of all AE/MS monitoring is that fluid movements excite acoustic signals, which in some fluid-rock systems might be not the case.

References

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3.3.8 Electrical methods (DC)

Direct current (DC) electrical methods generally involve the measurement of the resistivity distribution with depth using an array of electrodes placed in the ground. Traditionally, the electrical methods used an array of four electrodes, but the methodology has been advanced from this simple form to a multi-electrode array where the measurement process is computer controlled. The introduction in the 1990s of the multi-electrode arrays allows electrical resistivity imaging (ERI) of the subsurface to be carried out.

ERI systems generally consist of a resistivity meter, a switching relay, a portable computer (either to control or set-up the control system), electrode cables, and steel electrodes. A number of different electrode configurations are available including Wenner, Schlumberger, Dipole-Dipole, Pole-Pole and Square arrays.

The principle of the electrical resistivity method involves passing a DC current or a current with very low frequency (in order to avoid polarisation effects at the electrodes), I, into the ground through two metal stakes (electrodes), C1 and C2. The resulting potential difference or voltage, V, is measured across a second pair of electrodes, P1 and P2. The ratio V/I determines the ground resistance. Where the Wenner array is used, the apparent resistivity, ρa (measured in Ω·m), of the ground in the vicinity of the electrodes can be calculated from V/I and the spacing, a, between the four equi-spaced co-linear electrodes using the equation $\rho a = 2\pi a V/I$. With this system electrical resistivity measurements are obtained in a continuous profile along the length of the multi-core cable, initially with the unit electrode separation, a, set to the largest available multiple a. The electrode spacing is then decreased by a multiple of a, and a new profile of measurements obtained. This process is repeated at successively shallower levels as the electrode spacings (and hence depth of investigation) decreases, to produce a two-dimensional section of the electrical properties of the sub-surface. This arrangement is schematically shown in Figure 103.

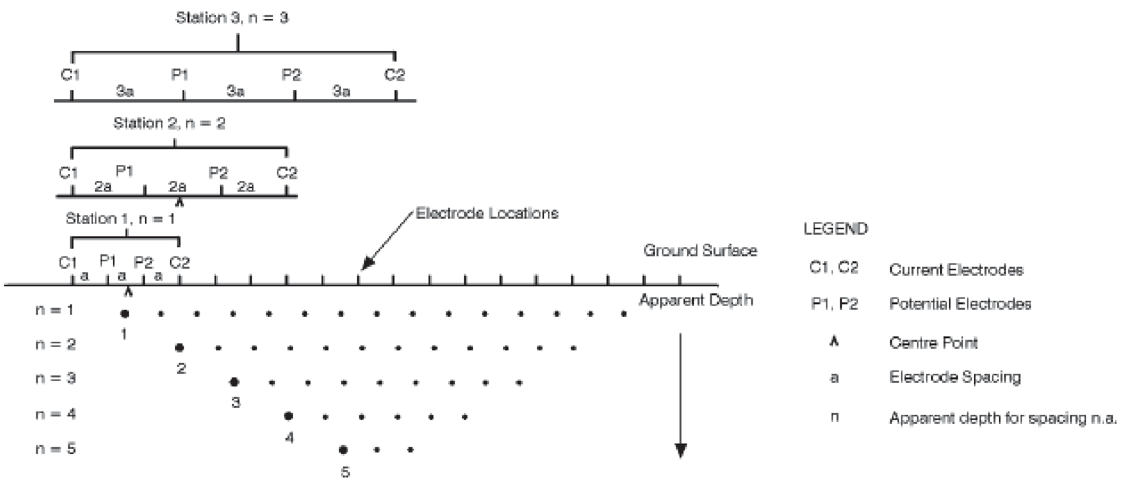

Figure 103: Schematic of electrical resistivity imaging approach.

The acquired data are normally presented as pseudo-sections, where apparent resistivity is plotted against level. This is only a qualitative method used for presentation of 2D resistivity data. The next step of processing is to compute specific resistivities and real depth from the pseudo-section using a 2D inversion scheme.

The methodology, however, generally produces information on the shallow subsurface, where the depth of investigation is dependent on the electrode spacing. In the example shown in Figure 104, where a minimum spacing of 3 m was used between electrodes, the depth of investigation is of the order of 40 m. Increasing the electrode spacing increases the depth of investigation but decreases the resolution of the method. With standard cables the depth of investigation is of the order of 60 m, however, some surveys have been successfully conducted to a depth of 200 metres.

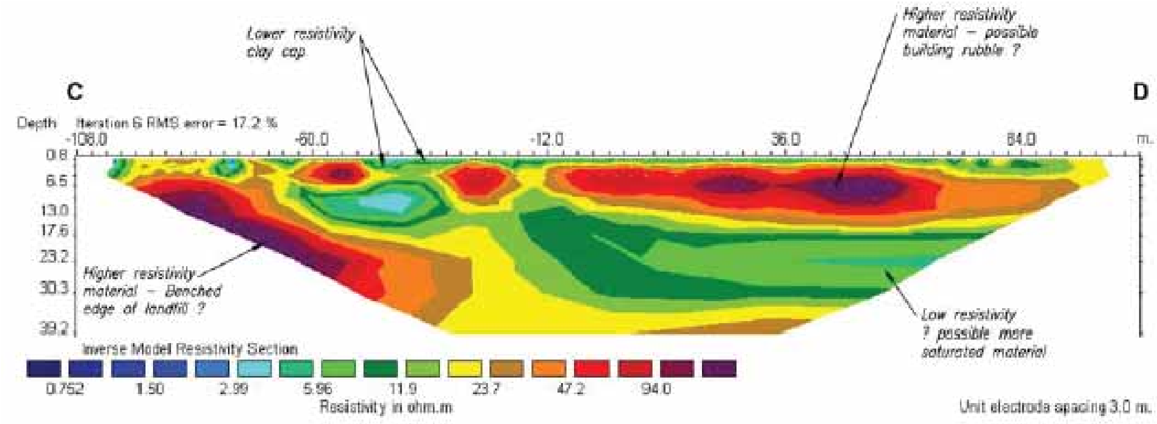

Figure 104: Schematic of electrical resistivity imaging approach.

Time-lapse ERI has been used successfully to investigate fluid movement through the shallow sub-surface.

Electrical resistance tomography (ERT) is another technique of imaging subsurface electrical conductivity. The method utilizes borehole casings as electrodes for both stimulating electrical current in the ground and measuring the electrical potentials that are induced. ERT was tested in Weyburn Phase II using a single borehole configuration as an economical monitoring alternative for situations that require less detail [273].

References

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3.3.9 Ground-Penetrating Radar

The basic principle of ground-penetrating radar (GPR) is to emit electromagnetic waves into the ground and record the reflected electromagnetic waves at the surface (same principle was described already at section 3.2.2 for boreholes). A GPR survey involves using a pulsed electromagnetic signal (radio wave) transmitted via a tuned frequency antenna that can penetrate soils, rock, concrete, ice and other common natural and man-made materials.

Under ideal conditions, GPR surveys can produce useful results over a depth of investigation of several tens of metres. In non-ideal conditions or where clays and/or saline (conductive) ground waters are present, the depth of investigation tends to zero. This depth limitation could make the use of GPR impossible with regards to repository conditions. However, the suitability of the method is site and target dependent. The depth of penetration achievable using GPR is also affected by ground characteristics, and obeys a frequency-dependent relationship. As the frequency of the electromagnetic waves increases, the degree of absorption increases and hence the signal attenuates more rapidly, reducing the depth of penetration. However, as frequency increases, the resolution of the technique improves, resulting in a more detailed image of the sub-surface. Hence, the selection of the correct transmitter frequency represents a compromise between maximum resolution and achieving the desired depth of penetration.

Variations in the electrical properties of sub-surface materials cause electromagnetic waves to propagate at different velocities. Interfaces in the sub-surface representing boundaries between materials with contrasting electrical properties (electrical permittivity and conductivity), such as geological or hydrogeological boundaries, reflect a fraction of the transmitted energy back towards the surface, whilst the remainder passes through the interface to deeper levels. The reflected wave (reflection event) is then recorded at a receiver antenna situated close to or coincident with the transmitter.

By carrying out a radar survey along a traverse line, a time or depth cross section (radar section) of the shallow sub-surface can be constructed. Signals incident at the receiver antenna are amplified, recorded, processed and displayed as a 2D section with signal amplitude plotted against arrival times. Converting from arrival time to depth is achieved by estimating or assuming the velocity of propagation of the electromagnetic waves through the sub-surface. Finally, the converted depth section, representing electrical properties of the ground, can be interpreted in terms of structure, lithology and fluids.

3.3.10 **Soil Gas Surveying**

Techniques for measuring soil gases were developed early in the 20th century for agricultural studies and for petroleum exploration. Within the last 5 years, soil-gas measurement has become an accepted environmental site screening tool. The technique is rapid, relatively cheap, and can provide a high yield of information.

The detectability of contaminants in soil gases is compound- and site-specific. Soil-gas technology is most effective in detecting compounds having low molecular weights, high vapour pressures, and low aqueous solubilities. These compounds volatilize readily and have favourable gas/liquid partition coefficients. Once in the gas phase, volatile compounds diffuse through the soil toward zones of lower concentration.

Degradation processes (e.g., oxidation or reduction) can eliminate or transform contaminants in the soil atmosphere. The susceptibility of a contaminant to degradation is influenced by such factors as soil moisture content, pH, redox potential, and the presence of microorganisms. Other site-specific characteristics affecting survey results are: soil type, air-filled porosity, depth to the source, barriers to vapour transport, and hydrogeology. Because site-specific factors influence contaminant concentrations, there is no generally applicable quantitative correlation between soil-gas concentrations and underlying contamination.

Soil-gas surveys are typically used to:

- identify contaminants and relative concentrations,

- identify sources and indicate extent of contamination,
- monitor the progress of site remediation projects,
- guide the location of sampling sites (e.g. soil borings or monitoring wells),
- long-term monitoring, and
- detect leaks through use of tracer compounds.

Soil-gas surveying is often used to detect contaminants from surface spills, leaking underground storage tanks, pipes, trenches, dry wells, or landfills. Contaminants from such sources frequently reach the water table, causing the groundwater to become a source of contamination to down gradient sites. The nature of the source will influence the dispersion of gas-phase contaminant vapours.

Soil-gas surveying is commonly used to detect contaminants such as chlorinated solvents and the lighter fractions of petroleum products. Inorganic contaminants that can be detected by soil-gas sampling include radon, mercury, carbon dioxide, nitrogen oxides, and hydrogen sulphide.

Soil-gas samples can be collected by active or passive methods. For active sampling, a probe is driven into the ground (e.g. Figure 105), withdrawn several inches, and soil gases are pumped from the subsurface into a sample container or through a sorbent medium.

Typically, active soil gas sampling systems require the removal of several hundreds of ml of soil gas. A new “micro-purge” system in which very small quantities of gas are collected (several ml) is currently being developed and tested [275].

For passive sampling, a sampler containing a sorbent with an affinity for the target analytes is placed in the ground for a period of time, and contaminants are collected by virtue of diffusion and adsorption processes.

Passive sorbants have been shown to collect a greater number of volatile organic compounds in soils than the active soil gas collection methods collected at the same site. The most commonly used technique for analysing soil-gas samples is gas chromatography (GC) in combination with a detector appropriate to the target analytes. GC analyses can be made on- or off-site. Complementary analysis can be made using laser Raman methods [276]. Raman scattering of light by molecules may be used to provide information on a sample's chemical composition and molecular structure [277].

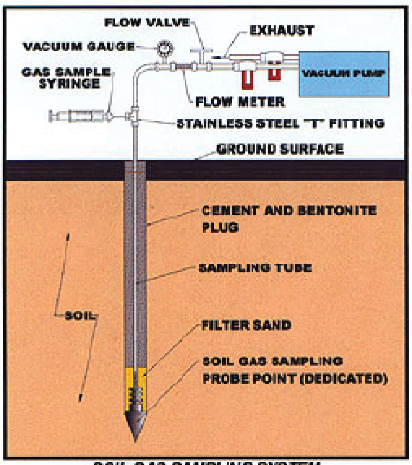

Figure 105: Illustration of a soil-gas sampling system.

The design of a soil-gas survey depends on the data required and the nature of the contamination. A feasibility study is recommended whenever possible, particularly for sites where little information is available. Such a study can be valuable in verifying the effectiveness of the method at the site, selecting the appropriate sampling and analytical methods, choosing the best sampling depth, and optimising other operational details. Because soil-gas surveying is an intrusive technique, precautions must be taken to avoid buried power lines, tanks, or other objects.

Because soil-gas results provide an indirect measure of primary contamination, data quality objectives (DQOs) for soil-gas surveys and the QA required need not be as strict as those for confirmatory sampling and analysis of soil or ground water. However, because most soil-gas survey objectives require comparison of data among points to determine patterns of relative concentration, the investigator must be able to determine whether differences in value are real or merely due to poor method precision. Consistency in procedures is essential, as are collection and analysis of replicate and blank samples and regular checks of instrument calibration. Materials that come into contact with samples should be inert and easy to decontaminate.

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3.3.11 **Surface movements monitoring**

Two typical types of surface-based monitoring systems are GPS (Global Positioning System) measurements to determine the extent of large-scale (horizontal) movements within the rock mass and to provide a measure of its stability by means of surface-based measuring stations and the surface precise levelling measurements to determine vertical movements (uplift). Surface levelling is also important for extensometers installed at surface to obtain the reference value.

The accuracy of the GPS measurements is about ±1 mm in a horizontal direction and in a vertical direction 2-3 mm. The accuracy of the surface levelling is around ±0.5 mm.

Case example:

Monitoring of the bedrock stability at the Olkiluoto site (site for spent nuclear fuel repository in Finland) consists of microseismic (MS) measurements, GPS-measurements and precise levelling measurements. A baseline for electronic distance measurements (EDM) was built in 2002. The baseline has been measured using EDM instruments in connection to the GPS observations [65].

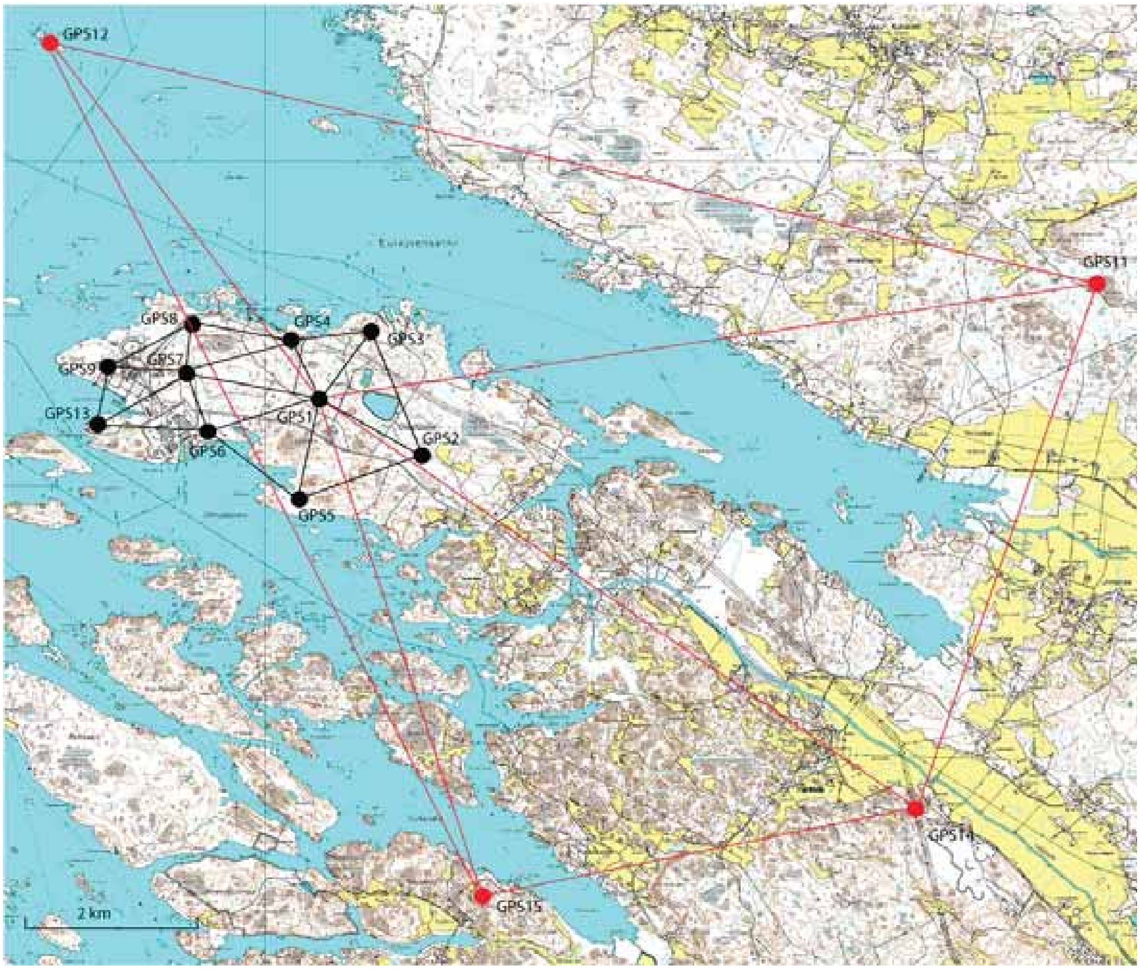

Figure 106: The local GPS monitoring networks at the investigation area of Olkiluoto. Black: Original network has been established in 1994 (GPS13 in 2003). Red: Pillars have been established in 2003 and 2005.

The GPS measurements have been carried out since 1995 resulting altogether in 28 measurement campaigns. The GPS network at Olkiluoto currently consists of 14 stations. According to the time series of the GPS results, 1/3 of the baselines at Olkiluoto have statistically significant change rates. However, the observed movements are smaller than ±0.20 mm/a. The precise levelling annual measuring campaigns have been conducted since 2003. The levellings have been divided into four loops, eight small GPS pillar loops and one line.[278]. Table 15 summarises the techniques described.

Table 15: Summary table:

Technique/ Method	Parameter	Application	Monitoring area	Measuring accuracy	Confidence
GPS	Displacement (horizontal)	Displacement changes	Ground surface above repository	1 mm (horizontal) 2 – 3 mm (vertical)	medium
Precise levelling	Displacement (vertical)	Displacement changes	Ground surface above repository	0.5 mm	medium

Context of application within Repository Monitoring:
Although the (most) repositories will be located deep at the bedrock, surface based monitoring is essential for possible large block movements. The GPS-system measures both vertical and horizontal displacement component, can easily cover large area and works also during the winter time when snow covers the surface.

References of use in previous experiences
- Olkiluoto site in Finland [240].

Limitations
Accuracy is not very good, and vertical accuracy is less than horizontal accuracy. Accuracy is also dependent on the strength of the signal.

Further developments
GPS-stations are typically measured manually which is time consuming. Alternative system could be the use of remote sensing (radar satellite technology), so-called InSAR-technique. More frequent (than GPS) measurements are possible but accuracy and winter conditions may be a problem.

References

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3.4 Remote monitoring

Subchapters 3.1, 3.2 and 3.3 have reviewed the diverse technologies available to monitor a geological repository from within the repository itself, from boreholes in its immediate vicinity or from the surface. This subchapter will focus on sensing technologies capable of monitoring the repository from a distance, needing no physical contact with the terrain. It must be noted, though, that the preclusion of physical contact with the terrain significantly restricts the number of features that can be monitored when compared with technologies described in other subchapters.

According to the type of data they produce, non-contact sensing technologies can be classified in the following main groups of methods:

- **Imaging methods:** different imaging sensors are used to produce georeferenced images showing the intensity of the electromagnetic radiation emitted or reflected by the terrain surface above a repository in diverse spectral bands (or polarisation modes, for radar images). Variations between successive images will allow monitoring of changes in the repository.

- **Modelling methods:** terrestrial laser scanners, mobile LiDAR sensors or digital photogrammetry are used to extract dense 3D point clouds of the terrain surface above a repository, from which digital terrain models are produced. InSAR can also produce high resolution digital terrain models, although in a totally different way. Variations between successive models will allow monitoring of changes in the repository.
- **Surveying methods:** stationary surveying instruments are used to determine with high accuracy the 3D coordinates of selected points on the terrain surface above a repository. Variations between successive surveys will allow monitoring of minute changes in the repository.
- **Mapping methods:** specific mobile sensors are used to measure the spatial variation of physical variables in the vicinity of a repository in order to produce maps that will show any anomaly generated by effect of the repository. Terrain motion maps can be produced by Differential InSAR techniques. Variations between successive maps will allow monitoring of changes in the repository.

These non-contact sensing technologies can have very different operating conditions, ranging from satellites orbiting the Earth to diverse types of airborne platforms, and even fixed locations with a good view of the terrain above a repository. These operating conditions will be discussed in section 3.4.1.

3.4.1 Non-contact sensing technologies

The following subsections describe in more detail different sensing technologies that could be useful for non-contact monitoring of a repository.

3.4.1.1 VNIR and SWIR imaging

Optical imaging in the VNIR (Visible and Near Infrared, 0.4-1.4 µm) and SWIR (Short Wave Infrared, 1.4-3 µm) ranges is a powerful technique to remotely acquire information both on the physical layout and the physical properties of materials constituting a target. The resulting images are a very intuitive way of organising position-related data regarding the spectral properties of materials, and can be very useful to characterise a repository location and to monitor subsequent changes (for instance, in mineral composition, vegetation, moisture content, soil properties, etc). The greatest disadvantage of optical imaging is its sensitivity to cloud cover.

Three basic types of images are generally considered, each one requiring a specific type of sensor for its acquisition:

- **Panchromatic** (PAN) images are single-channel greyscale images covering a substantial portion of the VNIR range in order to capture as much energy as possible to achieve maximum spatial resolution (Figure 107). Modern panchromatic sensors are based on linear CCD or CMOS arrays with TDI (Time Delay Integration), as the sensitivity of silicon matches the VNIR range. Traditional black & white photography is a particular case of panchromatic imaging, in which photographic film is sensitive to a certain portion of the visible spectrum. It is the oldest non-contact sensing technology, as photographs taken from balloons have been used since the 1860s.

Figure 107 – Panchromatic image from SPOT-5 satellite (Image credit: Satellite Imaging Corporation)

- **Multispectral** (MS) images are images containing several channels, each of which covers a certain band of the electromagnetic spectrum that has been specifically selected to provide information enabling the discrimination and characterisation of the expected objects of interest (Figure 108 bottom). Most multispectral sensors capture three or four bands in the VNIR, and a few of them capture additional bands in the SWIR, usually with lower resolution. Modern multispectral sensors operate in pushbroom fashion, and have a number of linear CCD or CMOS arrays with TDI (Time Delay Integration), each one fitted with its corresponding filter. Monolithic silicon devices are used for the VNIR bands, while hybrid HgCdTe CMOS sensors are used for the SWIR bands. This sensor design is much more robust than older whiskbroom scanners designs, which had moving parts. Standard colour photography is a particular case of multispectral imaging in which three channels are used to capture the red, green and blue bands of the visible spectrum.

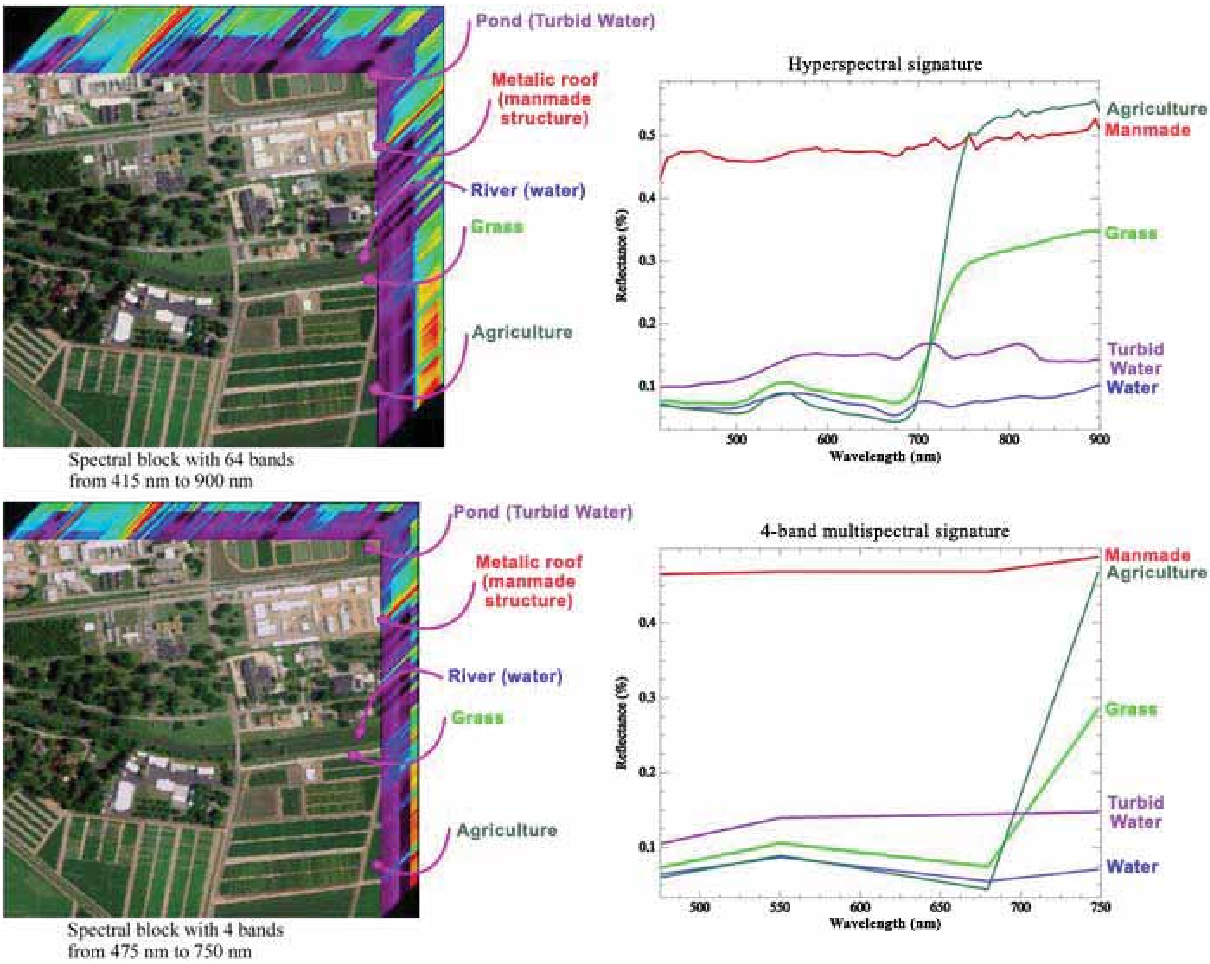


Figure 108 – Comparison of multispectral (bottom) and hyperspectral (top) signatures. The hyperspectral cube provides a true spectrum for each pixel. (Image credit: Auracle Geospatial Science, Inc.)

- **Hyperspectral** images are images containing a large number of channels, each covering a narrow band of the electromagnetic spectrum, and which, when stacked, form a three-dimensional hyperspectral data cube spanning a significant contiguous portion of the electromagnetic spectrum (Figure 108 top). Essentially, they contain a complete spectrum for each pixel of the image, which can help to identify minute differences between the corresponding points in the ground. Hyperspectral sensors were not widely used outside of military applications in the past, as they were basically experimental and produce very large datasets that were difficult to transfer, store and process, restricting their use to research applications. However, new hyperspectral imaging sensors have appeared recently in the market, targeting agricultural applications. These sensors are affordable and compact enough for installation in medium-size UAVs.

The three types of sensors are available for all platform types, and therefore the final choice will be dependent on the desired image resolution.

3.4.1.2 TIR imaging

TIR (Thermal Infrared) imaging provides data on the thermal infrared range of the electromagnetic spectrum, corresponding to wavelengths between 3.5 and 20 µm. It can be useful for different purposes, such as remotely measuring temperatures, detecting certain gases, and highlighting differences in composition of materials.

However, not all this range is useable, as absorption by water and other gases in the atmosphere (Figure 109) restricts aerial systems to two wavelength windows: 3-5 µm and 8-13 µm. Detectors have to be operated at very low temperatures to reduce signal noise, as the emitted thermal radiation being sensed is very weak. Two bands are typically acquired in most remote TIR imaging systems to allow compensation for atmospheric absorption. TIR imaging of a site location will be done most effectively using fixed or airborne thermal IR cameras, as satellite-mounted TIR sensors have too low resolution to be of practical use for this application.

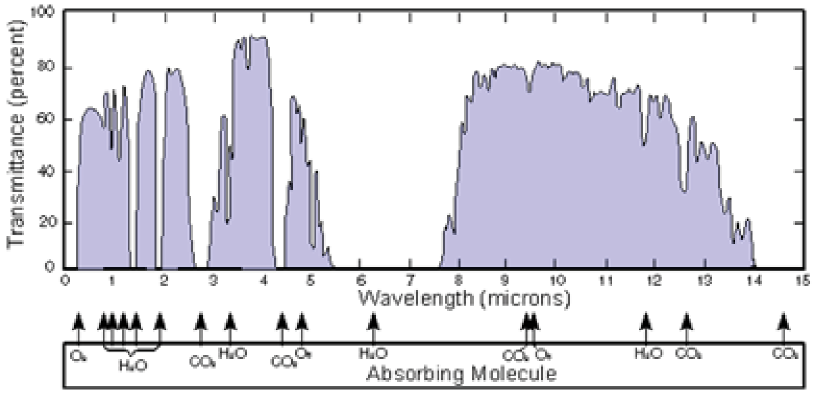


Figure 109 – Atmospheric transmission windows in the visible and the infrared

3.4.1.3 SAR imaging

SAR (Synthetic Aperture Radar) imaging obtains images in a way very different to optical images [282]. A special antenna attached to a mobile platform (Figure 110) radiates microwave pulses shaped as a wide, thin beam illuminating the ground with a certain incidence angle as the antenna moves relative to the terrain. The echo waveforms from the terrain that are received at the different antenna positions along its trajectory are coherently detected and stored, and then post-processed together to resolve individual elements (resolution cells) in an image of the target region.

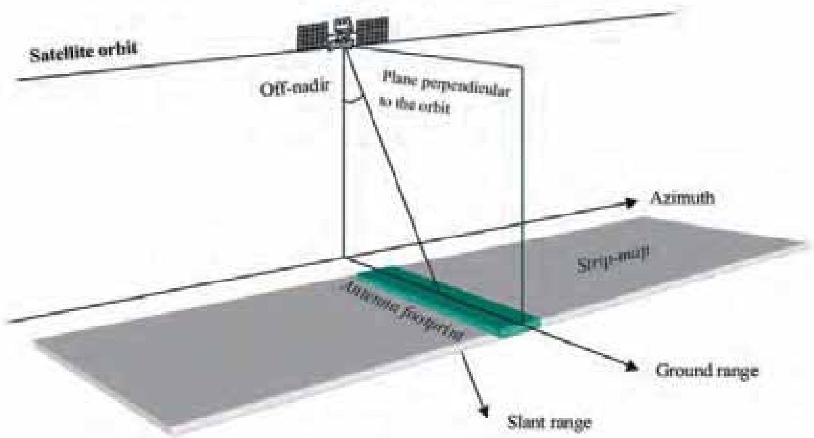


Figure 110 – Operating principle of Synthetic Aperture Radar (SAR)

The intensity of a pixel is proportional to the amplitude of the radiation backscattered toward the radar by the objects (scatterers) contained in the corresponding SAR resolution cell. This amplitude depends more on the roughness than on the chemical composition of the scatterers on the terrain. Typically, exposed rock and urban areas show strong amplitudes, whereas smooth flat surfaces (like quiet water basins) show low amplitudes, since the radiation is mainly mirrored away from the radar.

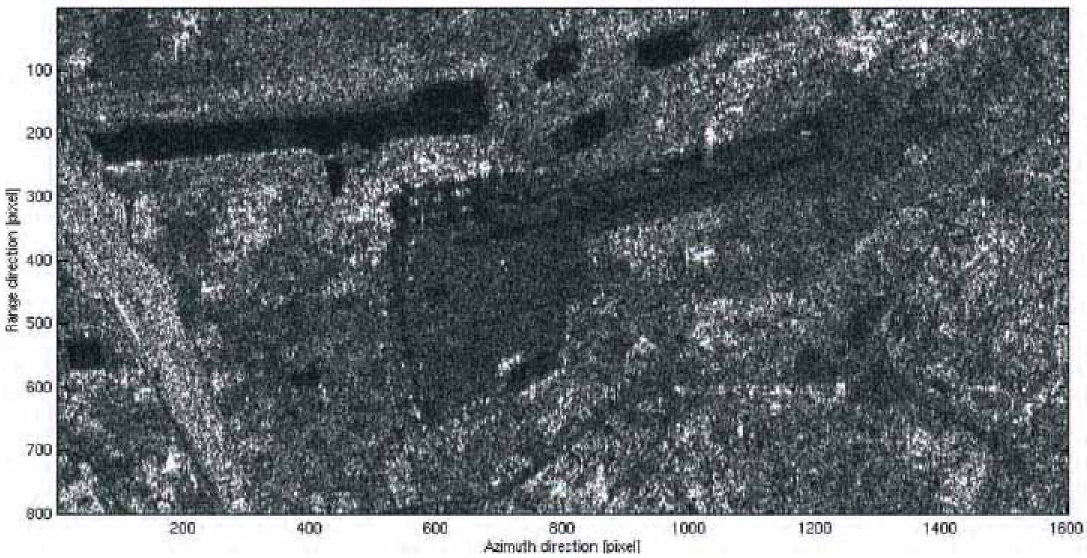


Figure 111 - ERS-2 SAR image of Linate airport: the speckle effect on the homogeneous fields surrounding the airport is clearly visible

SAR images suffer from the so-called "speckle" effect (Figure 111), which is a kind of "salt and pepper" noise that is inherent to coherent imaging systems. This effect can only be reduced by averaging a number of images acquired at different times or from slightly different look angles (Figure 112).

Figure 112 - Average of 60 ERS-1 and ERS-2 SAR images of Linate airport: the speckle effect on the homogeneous fields around the airport has disappeared

SAR images have the advantage over optical images that they are available night and day, and can penetrate smoke, dust, fog, thick cloud cover and even rain or hail. However, since radar interacts with ground features in a very different way to optical radiation, special care has to be taken when interpreting SAR images, in particular over sloped terrain, where the foreshortening effect can lead in extreme cases to the layover effect, in which the scatterers are imaged in reverse order and superimposed on the contribution coming from other areas (Figure 113). On the other side of the elevation profile, scatterers cannot be illuminated by the radar since they are in shadow. As a consequence, the corresponding SAR resolution cells do not contain any signal from the ground and they generate a dark gap on the detected image (Figure 113).

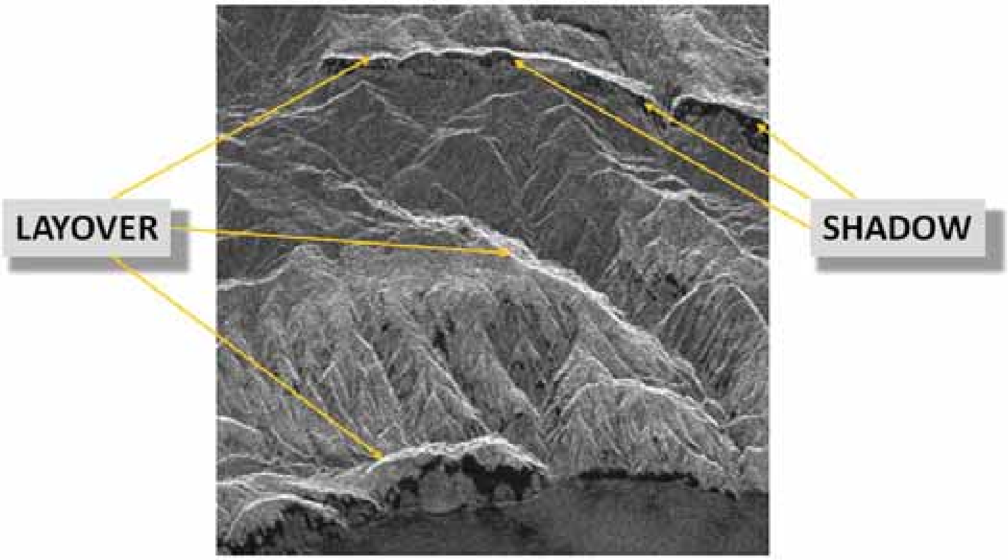


Figure 113 - SAR image of sloped terrain showing lay-over and shadow effects

As its principle of operation is based on the relative motion between the target and the antenna, SAR imaging requires airborne or satellite-mounted radar systems. It is not suitable for small UAVs, though, as the technology draws a substantial amount of power and requires a significant data processing capability.

3.4.1.4 DEM generation by InSAR

InSAR (Interferometric Synthetic Aperture Radar) is an advanced technique to obtain a digital elevation model (DEM) of the terrain based on the processing of two or more SAR images of the same area acquired with the same instrument from slightly different positions. This can be done simultaneously with two radars mounted on the same platform, as in the Shuttle Radar Topography Mission (SRTM), but more commonly it is done at different times by exploiting repeated orbits of the same satellite or using two satellites flying in tandem configuration. The distance between the two satellites (or orbits) in the plane perpendicular to the orbit is called the interferometer **baseline** and its projection perpendicular to the slant range is the perpendicular baseline (see Figure 114).

The first step in the process is the **co-registration** of the SAR images. This is usually done by resampling one of the images to match the geometry of the other. The **interferogram** of the two SAR images is then computed by cross-multiplying, pixel by pixel, the first image with the complex conjugate of the second. Thus, a pixel's amplitude is the amplitude of the first image multiplied by that of the second one, whereas its **interferometric phase** is the phase difference between the images.

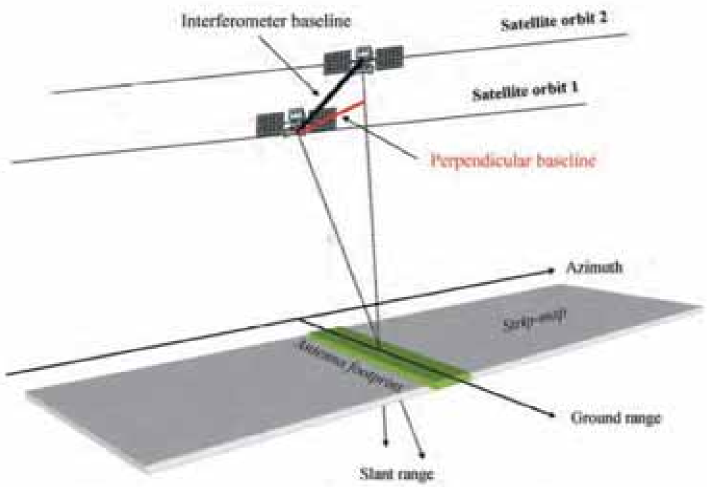


Figure 114 - Geometry of a satellite interferometric SAR system

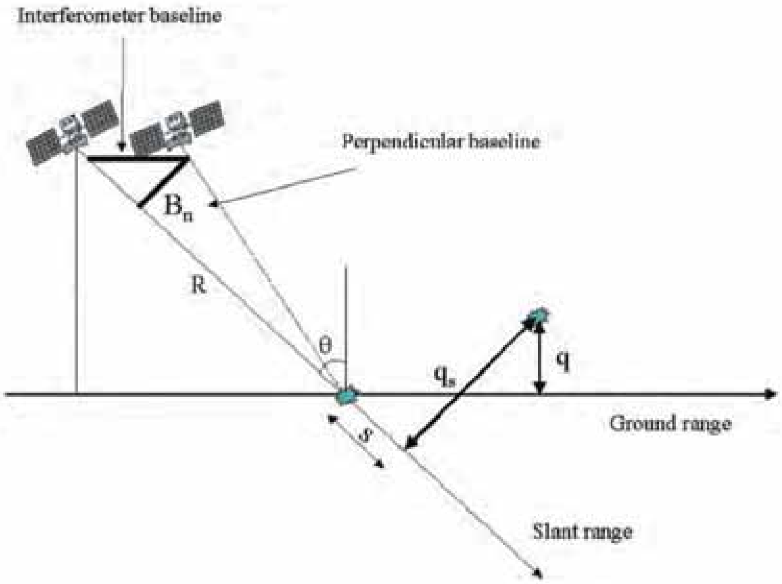


Figure 115 - Geometric parameters of a satellite interferometric SAR system

The interferometric phase variation between two contiguous resolution cells can be split into two contributions (see Figure 115): a phase variation proportional to the altitude difference **q** between the point targets, referred to a horizontal reference plane, and a phase variation proportional to the slant range displacement **s** of the point targets. As the perpendicular baseline is known from precise orbital data, the second phase term can be computed and subtracted from the interferometric phase. This operation is called **interferogram flattening** and, as a result, it generates a phase map proportional to the relative terrain altitude (Figure 116).

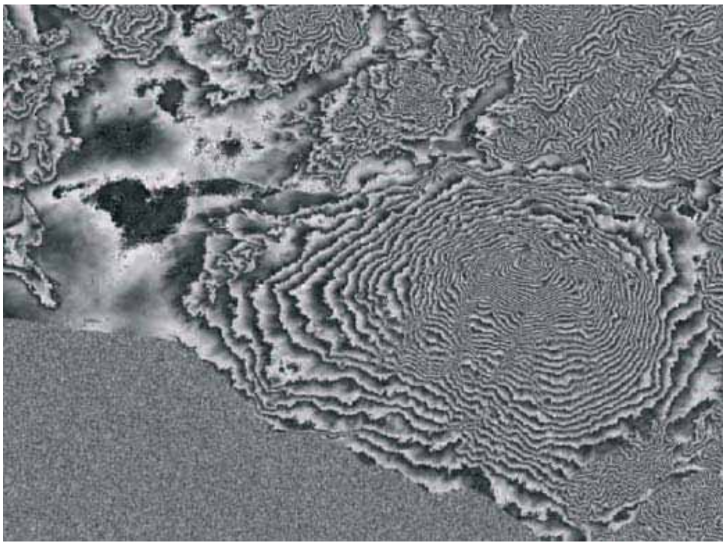


Figure 116 - Flattened interferogram of Mount Etna generated from ERS tandem pairs. The perpendicular baseline of 115 metres generates an altitude of ambiguity of about 82 metres.

The flattened interferogram provides an ambiguous measurement of the relative terrain altitude due to the 2π cyclic nature of the interferometric phase. The phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation, after deleting any integer number of altitudes of ambiguity (equivalent to an integer number of 2π phase cycles). The process of adding the correct integer multiple of 2π to the interferometric fringes is called **phase unwrapping**. Once the interferometric phases are unwrapped, an elevation map in SAR coordinates is obtained. The SAR elevation map should then be referred to a conventional ellipsoid (e.g. WGS84) and re-sampled on a different grid (UTM, for instance) to obtain a **DEM**. The DEM of Mount Etna shown in Figure 117 has been generated by unwrapping and resampling the flattened interferogram of Figure 116. Estimated vertical accuracy is better than 10 metres.

Figure 117 - Perspective view of Mount Etna as seen from the Northeast. The average of many ERS SAR images has been draped on the DEM.

3.4.1.5 Terrain motion measurement by DInSAR

DInSAR (Differential InSAR) is an advancedtechnique to measure the vertical component of terrain motion based on the processing of two SAR images of the same area acquired with the same instrument at different times. Suppose that some of the point scatterers on the ground slightly change their relative position in the time interval between two SAR observations (as, for example, in the event of subsidence, landslide, earthquake, etc.). In such cases a corresponding additive phase term, independent of the baseline, appears in the interferometric phase. This means that after interferogram flattening, the interferometric phase contains both altitude and motion contributions.

If a digital elevation model (DEM) is available, the altitude contribution can be subtracted from the interferometric phase, generating the so-called **differential interferogram**, (Figure 118) and the terrain motion component can be measured.

DInSAR can measure centimetre/millimetre-scale motions over timespans of days to years (as long as the coherence of the interferogram is maintained, which basically depends on terrain characteristics and rate of change), and has been used to monitor many different processes related to Earth surface deformations, such as:

- subsidence or heave effects above active or old mine works, tunnels, aquifers, oilfields, gas production sites, etc
- vertical surface displacements produced by an earthquake
- evolution of the magmatic chamber of a volcano
- activity of tectonic faults
- slope movement in mountain areas

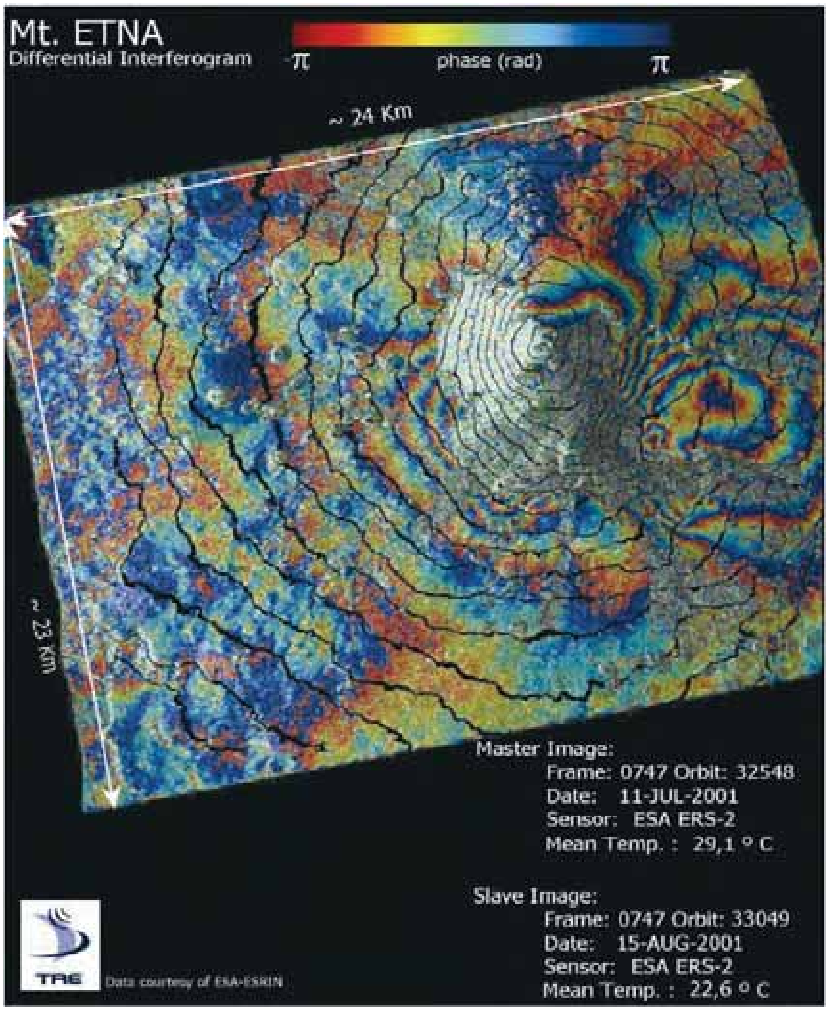


Figure 118 - The differential interferogram of the Mt Etna eruption that occurred in July 2001. The interferogram has been generated from two ERS-2 images taken before (11 July 2001) and after (15 August 2001) the eruption. The topography has been removed by means of an available DEM. Contour lines of the DEM are shown in black.

3.4.1.6 DTM generation by stereophotogrammetry

Stereophotogrammetry is an advanced technique (based on stereoscopy and photogrammetry principles) that allows to estimate the 3D coordinates of a large number of points on the surface of an object (a dense 3D point cloud) from the processing of two or more images of the object taken from different positions with a calibrated camera. This 3D point cloud can used to build a 3D model of the object or, for topographic applications, a DTM (Digital Terrain Model) or DEM (Digital Elevation Model).

The process for the determination of the height field is as follows (see Figure 119): Two pictures of the same area are taken from positions separated a distance CB. The distance between the point in question and a reference point is found in both pictures. These distances are labelled x and x' in the figure. The height difference Δh between the reference point and the point in question can then be calculated if the focal length v of the lens is known.

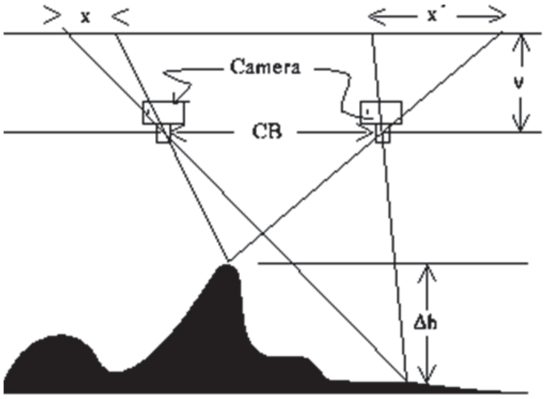


Figure 119 - Geometry involved when the stereoscopic method is used to figure the height field.

The cameras can be located anywhere, either on mobile platforms such as satellites, aircrafts, UAVs or handheld cameras, or on fixed terrestrial locations. While the accuracy obtained on known fixed locations is higher, there might be parts of the terrain that are occluded from view and therefore cannot be modelled. Mobile platforms, on the other hand, provide a more complete coverage of the terrain, although image processing becomes more complex as camera positions are not known with comparable accuracy. The use of ground control points may be necessary to correct distortions and scale/reference the stereo model.

Advances in software have made using the images from UAV cameras very easy. There are currently over 20 stereophotogrammetry software packages that can compute a 3D model of an object from a number of photographs (Figure 120). The most veteran are ELCOVISION 10E (from PMS AG / Leica Geosystems) and Photomodeler (from Eos Systems), which appeared in 1986 and 1994, respectively. Aside of DTM, other potentially interesting outputs from photogrammetry software are maps and diagrams, contour maps, volume measurements, ortho-photos and photo-mosaics.

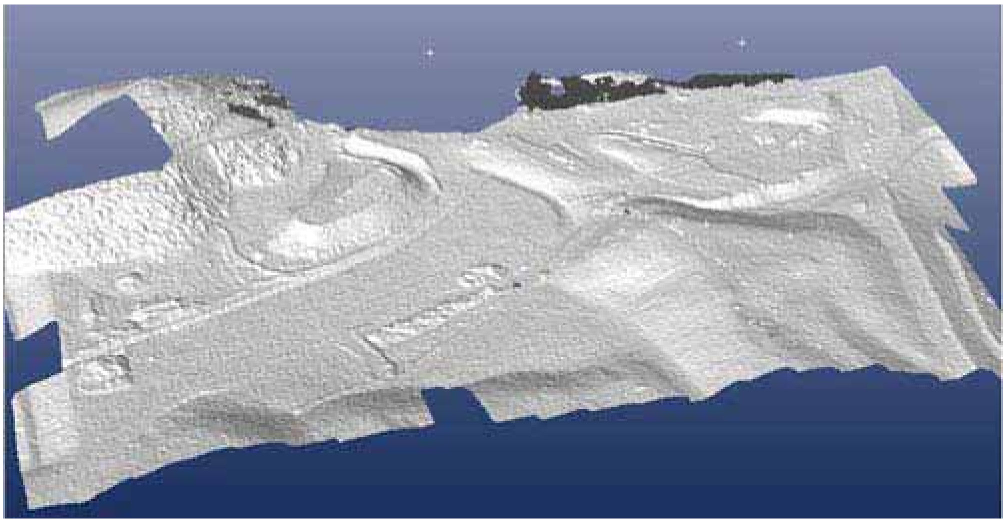


Figure 120 - Shaded view of a coal stockpile computed from aerial photos by Photomodeler

3.4.1.7 DTM generation by TLS

TLS (Terrestrial Laser Scanning) is a sensing technique based on the use of a laser scanner on a static vantage point on the surface of the earth. TLS instruments for civil engineering projects typically use “time-of-flight”, “phase based” (See Figure 121) or “waveform processing” technology to measure distances. The basic concept is similar to that used in total station instruments; using the speed of light to determine distance. However, there are significant differences in laser light wavelength, amount and speed of point data collected, field procedures, data processing, error sources, etc. Laser scanning systems collect a massive amount of raw data called a “point cloud.”

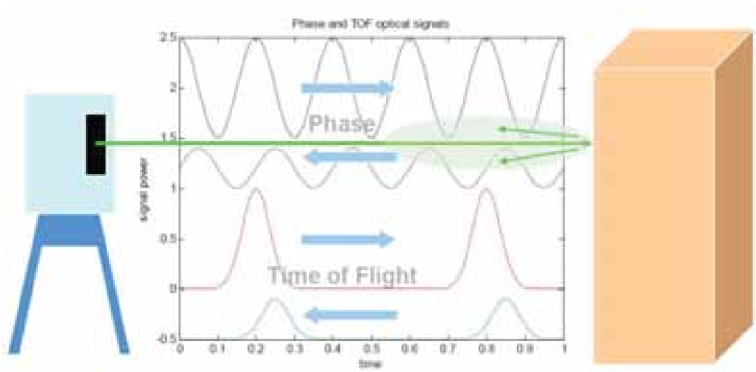


Figure 121 - Working principle of phase based and time-of-flight laser scanners (Image credit: UC Davis AHMCT Research Center: http://www.ahmct.ucdavis.edu)

Time-of-flight scanners are the most common type of laser scanner for civil engineering projects because of their longer effective maximum range (typically 125-1000m) and data collection rates of 50,000 points per second, or more. A time-of-flight laser scanner combines a pulsed laser emitting the beam, a mirror deflecting the beam towards the scanned area, and an optical receiver subsystem, which detects the laser pulse reflected from the object. Since the speed of light is known, the travel time of the laser pulse can be converted to a precise range measurement.

A phase based laser scanner modulates the emitted laser light into multiple phases and compares the phase shifts of the returned laser energy. The scanner uses phase-shift algorithms to determine the distance based on the unique properties of each individual phase. Phase based laser scanners have a shorter maximum effective range (typically 25-75m) than time-of-flight scanners, but have much higher data collection rates than time-of-flight scanners.

Waveform processing, or echo digitization laser scanners use pulsed time-of-flight technology and internal real-time waveform processing capabilities to identify multiple returns or reflections of the same signal pulse resulting in multiple object detection. Waveform processing laser scanners have a maximum effective range similar to that of time-of-flight scanners. Waveform processing scanners have trouble discriminating between returns of the same laser pulse from objects that are closely spaced. The discrimination limit is a function of laser emitter and receiver operating parameters. Returns from objects closer together than the laser scanner’s multiple object discrimination limit will create false points in the data.

The raw data product of a laser scan survey is a point cloud. When the scanning control points are georeferenced to a known coordinate system, the entire point cloud can be oriented to the same coordinate system. All points within the point cloud have X, Y, and Z coordinate and laser return Intensity values (XYZI format). The points may be in an XYZIRGB (X, Y, Z coordinate, return Intensity, and Red, Green, Blue colour values) format if image overlay data from an internal or external digital camera is available (Figure 122).

Figure 122 - Point cloud of a power station with RGB values (Image credit: Dale Stockstill and Associates)

Just as with reflectorless total stations, laser scan measurements that are perpendicular to a surface will produce better accuracies than those with a large angle of incidence to the surface. The larger the angle, the more the beam can elongate, producing errors in the distance returned. Data points will also become more widely spaced as distance from the scanner increases and less laser energy is returned. At a certain distance the error will exceed standards and beyond that no data will be returned. The low reflectance and the roughness of natural surfaces can reduce achievable range in practice, and vegetation cover can contribute significantly to increase measurement noise. Atmospheric factors such as heat radiation, rain, dust, and fog will also limit scanner effective range.

While terrestrial laser scanning may result in less field time to complete complex projects, data extraction and production of usable Computer Aided Design and Drafting (CADD)/Digital Terrain Model (DTM) format products currently takes considerable office time. The field to office processing time ratio increases with point density, complexity of the objects being scanned and deliverable detail.

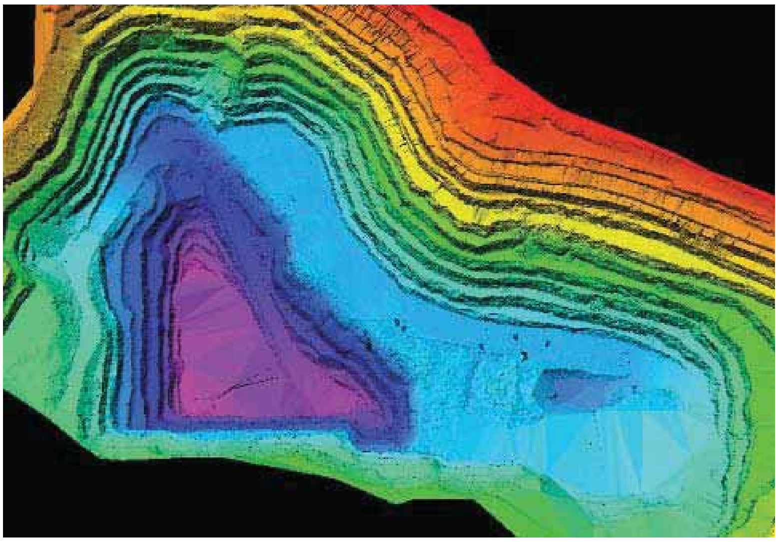
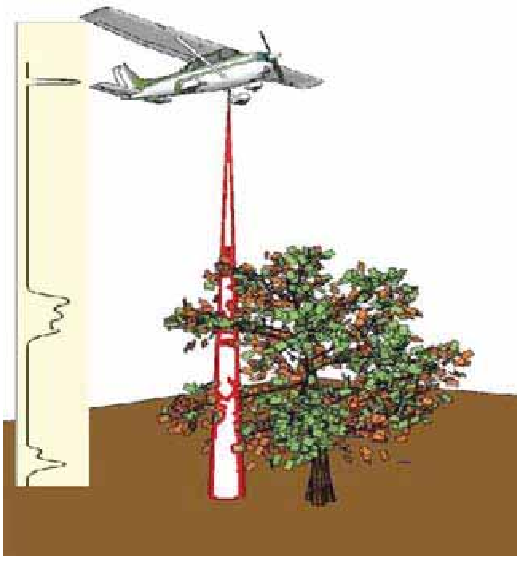


Figure 123 - DTM generated from TLS point clouds

(Image credit: Optech Inc)

3.4.1.8 DEM generation by LiDAR

LiDAR (Light Detection and Ranging) is a technology that constitutes the light-based analogous to RADAR. Airborne LiDAR can be used to simultaneously obtain topographic profiles of both terrain surface and forest canopy (Figure 125), by performing time-of-flight measurements of the distance between the aircraft and the ground under the flight path. Corrections for the attitude and trajectory followed by the aircraft are computed from inertial and GPS data registered in-flight. The point clouds obtained by this technique (Figure 125) are well suited to the generation of DEMs of the terrain surface (Figure 126).



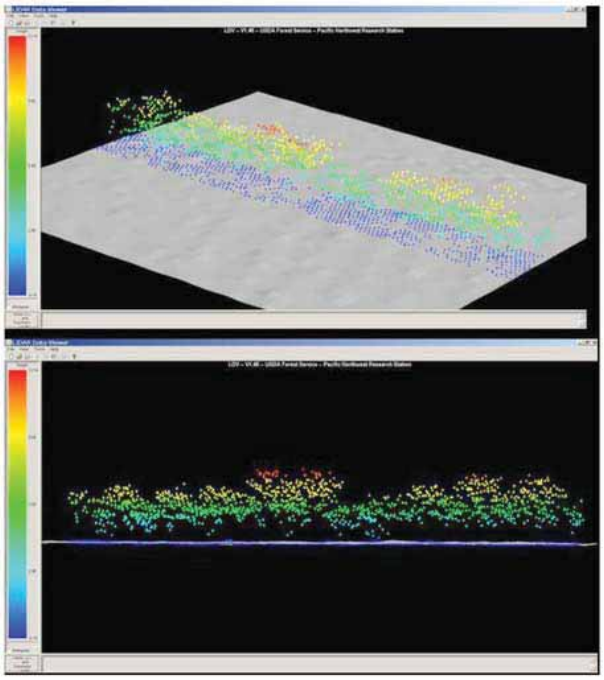


Figure 124 - How LiDAR works First steps in interpreting the data

(Image credit: www.forest-carbon.org)

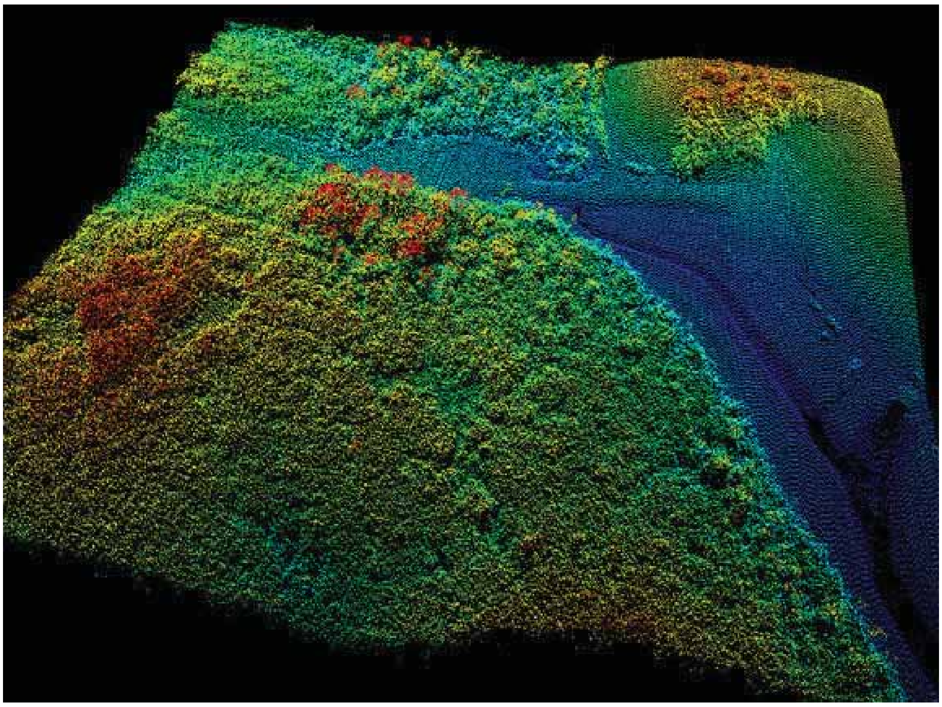


Figure 125 - Example of lidar point cloud (Image credit: www.forest-carbon.org)

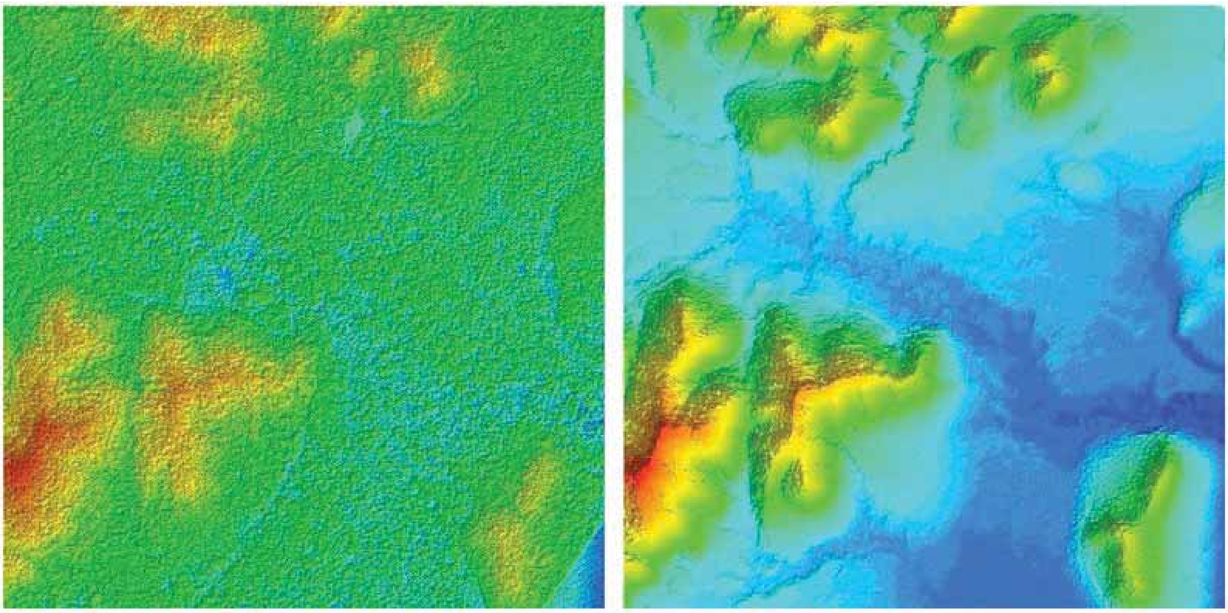


Figure 126 - Extremely accurate digital elevation models are obtained from LiDAR (Image credit: www.forest-carbon.org)

3.4.1.9 Topographic surveying

This method is based on the use of standard surveying tools such as total stations on static vantage points on the surface of the earth. A total station is a surveying instrument combining a motorised theodolite with an electronic range finder, which can compute with high accuracy the position of a reflector relative to the instrument. Robotic total stations can be fully controlled from a computer in order to automatically search and determine the 3D coordinates of a number of reflectors distributed over a target, essentially becoming an autonomous position sensing system able to monitor minute displacements (Figure 127).

The capability of robotic total stations to feature motorised axis movements combined with the development of monitoring software led to an innovative geotechnology concept: **monitoring**

stations. When designing a construction project, it is essential to include the need for periodic position controls. In applications such as the construction of bridges, tunnels, mines, high-rise buildings and dams, it is crucial to monitor positional changes over time, observing any small movements and emitting early warnings to alert one to the potential danger of structural failure.

Figure 127- Robotic total station for automatic dam displacement monitoring in its shelter. (Image credit: Department of Geodesy and Geomatics Engineering. Univ. of New Brunswick)

Monitoring stations systematically measure the position of all the survey monuments located on a monitored structure, without the need of an operator. The effective monitoring of projects involves statistical analysis of several epochs of observations of the monuments to millimetre-level accuracy. Manufacturers such as Leica, Sokkia, Trimble and Topcon offer total stations designed specifically with the requirements of survey monitoring in mind, namely:

- very high angular accuracy, usually 1" or better
- very high distance accuracy, usually 1mm + 1ppm or better
- servo-equipped, with software that allows for repeated measurements of control points at a set interval
- highly accurate prism finder
- ability to receive external power, allowing the station to operate 24/7
- ability to communicate the measurements to a remote computer, allowing the station to function in remote locations without the need of an operator.

Although total stations are very accurate, they can only provide a sparse cloud of points, as a relatively expensive reflector is required for each monitored point. Therefore, they can be used as a kind of “ground truth” reference for another sensing system that measures a much denser cloud of points.

3.4.1.10 Geophysical surveying

Geophysical methods such as magnetic, gravity/micro-gravity and electromagnetic surveying may be undertaken using airborne sensors. The discussion of these methods was included with the general discussion of these techniques in subchapter 3.3, and will not be repeated here.

Some of the techniques describe above, such as laser scanners, LiDAR, SAR and total stations are active, that is, they are based on the emission of electromagnetic radiation towards the observed subject, and the measurement of reflected or backscattered radiation, and can be used by night. The other techniques are considered passive, as they rely on the detection of the electromagnetic radiation emitted, or reflected from natural sources such as sunlight, by the observed subject, or on the measurement of its natural magnetic, electromagnetic or gravity fields.

References

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3.4.2 Platforms for non-contact sensing technologies

The non-contact sensing technologies described above have highly diverse operating conditions. Some may require a particular type of satellite, some other may have to be operated from an aerial platform that should fly at a specified altitude, others must be set at fixed terrestrial locations, a few may be used on any type of mobile platform… etc. All those different operating conditions can be grouped in the following main types of platform:

- Earth observation **satellites**.
- Specialised remote-sensing **aircrafts**.
- Sensorised **UAV** (Unmanned Aerial Vehicles) with autonomous flight capability.
- **Static ground locations** with a good view of the terrain above the repository.

Of course, not all of these platform types are suitable for every sensor, due to limitations on weight, size, stability, operating cost, etc. The following sections describe the different choices available for each type of platform.

3.4.2.1 Sensing from Earth observation satellites

According to their orbit characteristics, there are two main types of artificial satellites for Earth observation: geostationary and LEO satellites.

Geostationary satellites orbit the Earth 35.786 km above the equator in order to have an orbital period of exactly one sidereal day (23h 56m 4s), therefore when viewed from the Earth they appear to be fixed in the sky. This makes them ideally suited for applications requiring permanent monitoring of large regions, such as meteorological observation. Unfortunately, their extremely high altitude prevents the acquisition of images with high spatial resolution, so they are not really useful for the monitoring of a site.

LEO (Low Earth Orbit) satellites orbit our planet at altitudes ranging from about 400 to 800 km, with orbital periods of about 90 minutes. Their orbits are usually polar, in order to be able to observe all or most of the Earth, and revisiting periods for a site may vary from less than one day up to a few weeks, depending on the site's latitude, as well as on the field of view of the satellite and its capability to slant its view to observe nearby tracks. Their lower altitude allows the acquisition of images with sufficiently high spatial resolution, enabling their use for the remote monitoring of a site.

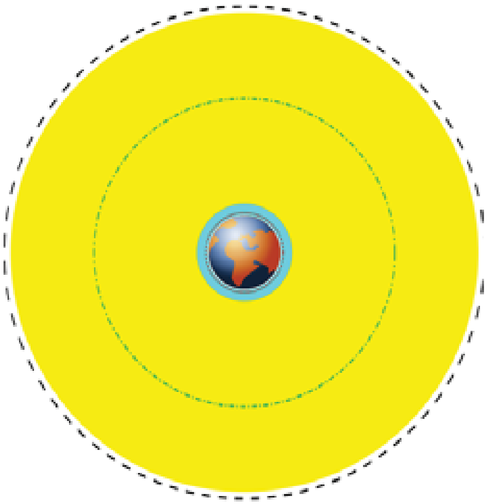

Figure 128 - Various Earth orbits to scale; cyan represents Low Earth Orbit, yellow represents medium earth orbit, the black dashed line represents geosynchronous orbit, the green dash-dot line the orbit of Global Positioning System (GPS) satellites, and the red dotted line the orbit of the International Space Station (ISS).

Most Earth observation satellites provide one of three main types of imagery: panchromatic, multispectral and radar, although many of them provide both panchromatic and multispectral. Each type of image has its own range of applications, as was explained in section 3.4.1.1.

Panchromatic images are single-channel greyscale (black&white) images covering a large spectral range in order to capture as much energy as possible to obtain maximum detail.

Spatial resolution can be as high as 0.41 m/pixel for the GeoEye-1 or 0.46 m/pixel for the WorldView-2, although commercially available images are limited to a maximum resolution of 0.5 m/pixel by the US Government. Even higher spatial resolutions will be possible with newer generations of satellites to be deployed shortly (e.g. 0.31 m/pixel for the WorldView-3 or 0.34 m/pixel for the GeoEye-2, both planned for launch in 2013).

Table 16 lists the characteristics of the panchromatic band of the main current and future satellites.

Multispectral images are images containing several channels, each of which covers a specific band of the electromagnetic spectrum. These bands are specifically selected to provide valuable information enabling the discrimination, identification and characterisation of the expected objects of interest of an Earth observation satellite (land use, soil, vegetation, moisture, mineral composition of the ground, shallow waters, etc), within the atmospheric windows shown in Figure 109. Multispectral images always cover at least the VNIR (Visible and Near Infrared) range, and some satellites also feature bands in the SWIR (Short Wavelength Infrared) and the TIR (Thermal Infrared) ranges. The spatial resolution of multispectral images is typically several times lower than that of panchromatic images of the same satellite, and it is often heterogeneous, as VNIR bands tend to have more resolution than SWIR bands, and much more than TIR bands.

Table 16: Details of the panchromatic band of current and future satellites

SATELLITE	Altitude (km)	Panchromatic (nm)	Resolution (m/pixel)	Swath (km)	Revisit (days)
DEIMOS-2 (2014)	620	450-900	1	12	2
EO-1 ALI	705	480-690	10	37	2-5
EROS-A	510	500-900	1,9	14	4
EROS-B	510	500-900	0.7	7	4
FORMOSAT-2	891	450-900	2	14	1
FORMOSAT-5 (2014)	720	450-900	2	24	1
GEOEYE-1	681	450-800	0.41 (0.5)	15.2	3
GEOEYE-2 (2013)	681	450-800	0.34 (0.5)	14.5	3
IKONOS	681	526-929	0.82 (1)	11.3	3-5
INGENIO (2014)	670		2.5	60	3
KOMPSAT-2	685	500-900	1	15	3
LANDSAT-7	705	520-900	15	185	16
LANDSAT-8/LDCM (2013)	705	500-680	15	185	16
PLEIADES	694	480-830	0.5	20	1
QUICKBIRD	482	445-900	0.61	16.5	2-4
RESOURCESAT-2 (LISS-IV)	822	620-680	5.8	70	5
SPOT-5 (HRG)	822	480-710	2.5	60	2.4-3.7
SPOT-6/7	694	480-710	1.5	60	1
THEOS	822	450-900	2	22	1-5
WORLDVIEW-2	770	450-800	0.46 (0.5)	16.4	1-3
WORLDVIEW-3 (2014)	617	450-800	0.31 (0.5)	13.1	< 1

The highest spatial resolution currently available for VNIR bands is 1.65 m/pixel (GeoEye-1 satellite), although it is expected to reach 1.24 m/pixel with deployment of WorldView-3 satellite at the end of 2013.

Table 17 lists the number of bands, resolution and swath of the multispectral images provided by the main current and future satellites.

SAR (Synthetic Aperture Radar) images are inherently greyscale, as the intensity of each pixel represents the proportion of microwave backscattered from an area on the ground, which depends on several factors: terrain roughness, ground moisture content, frequency and polarisation of the radar pulses, incident angle of the radar beam, and existence of scatterers. However, false-colour SAR images can be obtained by combining images obtained with different acquisition parameters or at different times. SAR images have the advantage over optical images that they are available night and day, and under smoke, dust, fog, thick cloud cover or even rain or hail.

SAR satellites typically have several observation modes, with different resolutions and swaths. Figure 129 shows the many different beam modes of RADARSAT-2 satellite, which are quite similar to the modes of other modern SAR satellites.

Table 17: Details of the multispectral bands of current and future satellites

SATELLITE	Altitude (km)	Bands	Resolution (m/pixel)	Swath (km)	Revisit (days)
DEIMOS-1 / UK-DMC2	669	3 VNIR	22	660	2-3
DEIMOS-2 (2014)	620	4 VNIR	4	12	2
EO-1 ALI	705	6 VNIR 3 SWIR	30 30	37	2-5
FORMOSAT-2	891	4 VNIR	8	14	1
FORMOSAT-5 (2014)	720	4 VNIR	4	24	1
GEOEYE-1	681	4 VNIR	1.65	15.2	3
GEOEYE-2 (2013)	681	4 VNIR	1.36	14.5	3
IKONOS	681	4 VNIR	3.2 (4)	11.3	3-5
INGENIO (2014)	670	4 VNIR	10	60	3
KOMPSAT-2	685	4 VNIR	4	15	3
LANDSAT-7	705	4 VNIR 2 SWIR 1 TIR	30 30 60	185	16
LANDSAT-8/LDCM (2013)	705	5 VNIR 3 SWIR 2 TIR	30 30 100	185	16
PLEIADES	694	4 VNIR	2	20	1
QUICKBIRD	482	4 VNIR	2.44	16.5	2-4
RAPIDEYE	630	5 VNIR	6.5	77	1
RESOURCESAT-2 (LISS_IV)	822	3 VNIR	5.8	23.5	5
SENTINEL-2 (2013)	786	4 VNIR 6 SWIR 3 AC	10 20 60	290	2-5
SPOT-5 (HRG)	822	4 VNIR	10	60	2.4-3.7
SPOT-6/7	694	4 VNIR	6	60	1
TERRA (ASTER)	705	3 VNIR 5 TIR	15 90	60	16
THEOS	822	4 VNIR	15	90	1-5
WORLDVIEW-2	770	8 VNIR	1.84 (2)	16.4	1-3
WORLDVIEW-3 (2014)	617	8 VNIR 8 SWIR 12 CAVIS	1.24 3.7 30	13.1	< 1

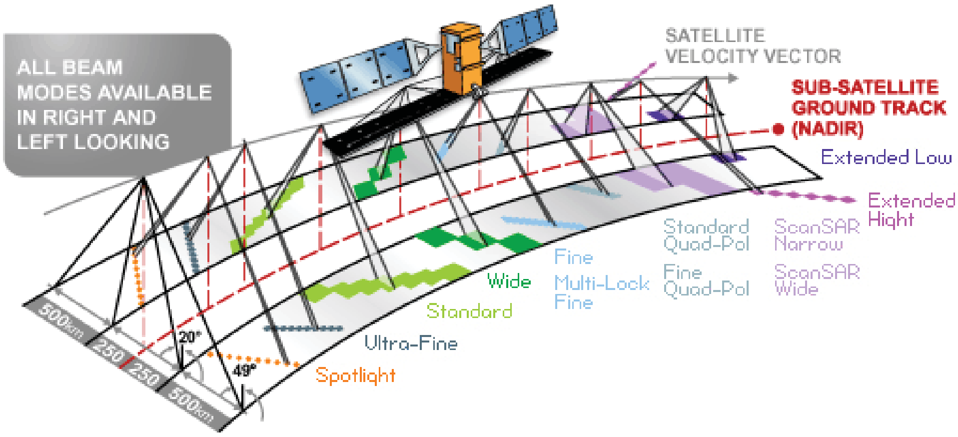

Figure 129 - Different beam modes of RADARSAT-2 satellite (Image credit: Vigisat)

The spatial resolution of the previous generation of SAR satellites (ERS-1/2, ALOS, ENVISAT, etc) was not particularly high (15-20 m). However, currently available SAR satellites are able to acquire images with spatial resolutions as high as 1 m, so the detail of their images should improve considerably over the images provided by classic satellites such as ERS-1/2, which are no longer operational.

Table 18 lists some characteristics of the main current and future SAR satellites.

Table 18: Details of the SAR images of current and future satellites

SATELLITE	**Altitude (km)**	**Band**	**Wavelength (cm)**	**Resolution (m/pixel)**	**Swath (km)**	**Revisit (days)**
ALOS-2 (2013)	628	L-band	25	1-100	25-350	14
COSMO-SkyMed	620	X-band	3.1	1-100	10-200	10h
KOMPSAT-5	550	X-band	3.1	1-20	5-100	28
PAZ (2013)	514	X-band	3.1	1-15	5-100	1
RADARSAT-2	798	C-band	5.6	1-100	18-500	1-5
Sentinel-1 A (2013)	693	C-band	5.6	5-20	80-400	3
TerraSAR-X/TanDEM-X	514	X-band	3.1	1	10	2

TerraSAR-X and TanDEM-X are almost identical satellites, flying in tandem along two intertwined orbits that keep an almost constant separation between them. In this way, the two satellites produce image pairs that are guaranteed to have sufficient coherence for InSAR applications. Other satellites (COSMO-SkyMed) are in fact constellations of several satellites flying along the same orbit with fixed angular separations, in order to have a short revisit period and facilitate the acquisition of image pairs for InSAR applications.

Figure 130 shows currently operational and future planned satellite missions with SAR imaging capability, both for commercial and military use. The trend to build constellations of identical satellites flying in tandem is clear, as it significantly decreases revisit periods, simplifies satellite operation and provides more opportunities for the application of SAR interferometry.

There are some experimental sensors that provide other types of data. The most interesting ones are:

- NASA’s Hyperion hyperspectral sensor onboard Earth Observing-1 (EO-1) satellite, which provides 220 hyperspectral bands from 400 to 2500 nm, each one with a spectral width of 10 nm and a spatial resolution of 30 m. Scan swath is 7.7 km.
- NASA’s Calipso, which provides LiDAR images of the atmosphere.

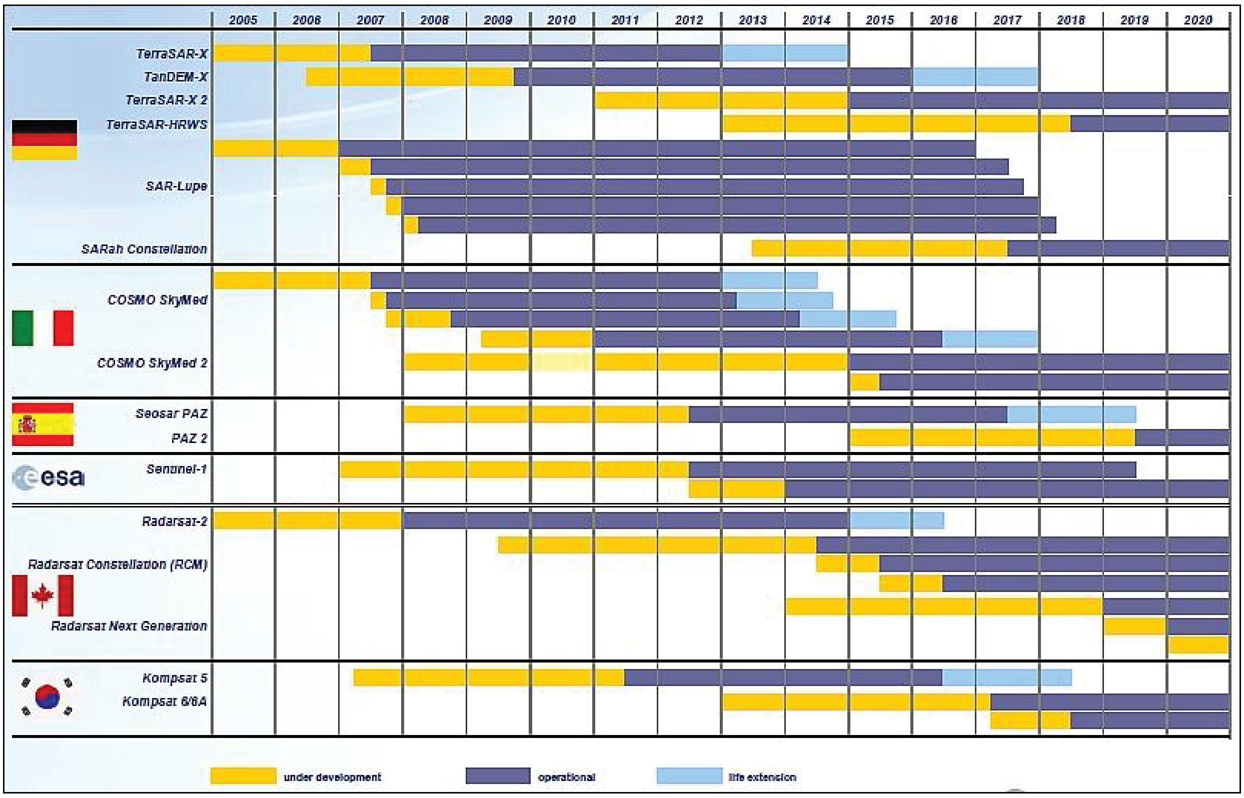

Figure 130 - Overview of SAR imaging from space (image credit: EADS Astrium)

3.4.2.2 Aircraft-based airborne sensing

Aircraft-based sensing is typically required when the effective resolution that can be obtained with satellite-based sensing is not sufficient for the intended use. There is a great variety of sensors specifically designed for airborne operation. The most commonly used are: aerial large-format photography cameras, VNIR and SWIR multispectral imagers, hiperspectral imagers, TIR imagers, SAR imagers, and LiDAR sensors.

The main problem with this type of platforms is their high operational costs, as the specialised aircrafts required to properly install the sensors and their processing hardware are scarce and expensive, and sometimes have to be flown in from distant places. Besides, crews need to be quite experienced to perform their duty well, adding to the cost.

3.4.2.3 UAV-based airborne sensing

Aerial photogrammetry was once the sole purview of full-size manned aircraft with expensive aerial photogrammetric cameras. Now relatively inexpensive and intelligent UAVs (fixed-wing and multi-rotor) that can carry good-quality digital SLR cameras have changed who has access to aerial mapping systems, instead of limiting their use only to large budget projects. Examples of UAV photogrammetry are golf course mapping, large accident scene diagramming, mining documentation, and stockpile volume measurement.

UAVs are very interesting platforms to carry out periodic non-contact monitoring of a site area, as they can be operated either by remote-control or in fully autonomous mode following a pre-programmed path, and their operational costs are significantly lower than those of manned aircrafts. There are many different types of UAVs in the market, ranging from almost full-size combat aircrafts capable of carrying large sensors such as SAR systems to small quadricopters only capable of carrying a very light payload.

However, the market is now offering very interesting hovering UAVs, with almost any-weather flying capability, that do not require an airfield for take-off or landing, that seem ideal for the type of image-acquisition flights that will be required for the monitoring of the repository. Two of the more popular ones are the hexacopter Aibot-X6 and the quadricopter Aeryon Scout.

Figure 131 - Quadricopter Aeryon Scout from Aeryon

Figure 132 - Hexacopter Aibot-X6 from Aibot

Although the most common type of sensor for small UAVs is a standard digital photographic camera, as it allows building highly-detailed DTMs draped with full-colour terrain images by using stereophotogrammetric techniques, these UAVs could also incorporate other sensors, such as FPA (Focal Plane Array) TIR cameras, that would allow to create false-colour images showing ground temperature distribution over the site area, or new compact and affordable hyperspectral sensors suitable for small UAVs that have recently appeared in the market, targeting non-military applications such as agriculture, remote sensing, mining & mineral exploration, etc.

3.4.2.4 Sensing from fixed locations

When selecting a fixed terrestrial location from which to carry out non-contact sensing over a moderately large area, the simplest choice would be to install the sensors on an elevated place providing a good view of the site. A well known example of such elevated locations are forest watchtowers, which allow the installation of early fire detection systems based on VNIR and/or

TIR cameras. Another typical example of stationary locations are the fixed bases built in the vicinity of dams for the setting up of the total stations used in periodic inspections of dam deformation.

Therefore it is reasonable to assume that certain configurations of fixed terrestrial locations might be ideal for the installation of different types of non-contact sensing devices that would allow monitoring some features of the ground atop a given site. The details of the design would depend on the particular conditions of the site location.

The methods that would *a priori* be most suitable for use on fixed terrestrial locations are all imaging techniques but SAR (as it requires relative motion between the target and the antenna), as well as DTM generation tools such as stereophotogrammetry, topographic mapping tools such as TLS and topographic surveying tools such as total stations.

Fortunately, terrestrial radar interferometry (TRI) systems have been developed which are capable of generating high accuracy (sub-millimetric) displacement measurements at long distances (up to 10 km) and across a wide field-of-view (up to 360 °).

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3.4.3 Applications of satellite-based imaging

NASA's Terra satellite carries a number of imaging instruments, one of which is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [290]. ASTER is the only high-resolution instrument on the Terra satellite and is used with four other instruments, which monitor the electromagnetic energy emitted from the surface of the Earth at moderate to coarse spatial resolutions.

The instrument consists of three separate subsystems, each of which has its own telescope or telescopes that view the Earth in a different part of the energy spectrum. One of the subsystems views the Earth in the visible and near-infrared, the second views in the shortwave infrared, and the third views in the thermal infrared. The spatial resolution of this system is frequency dependent and is 15 m in the visible and near infrared, 30 m in the shortwave infrared, and 90 m in the thermal infrared. Each ASTER image covers an area of 60 km by 60 km [291].

Figure 133 shows three false-colour ASTER satellite images (15m) of the Saline Valley area, California. Each image displays data from a different spectral region, and illustrates the complementary nature of surface compositional information available as a function of wavelength. The left image displays visible and near infrared bands 3, 2, and 1 in red, green, and blue (RGB). Vegetation appears red, snow and dry salt lakes are white, and exposed rocks are brown, gray, yellow and blue. Rock colors mainly reflect the presence of iron minerals, and variations in albedo. The middle image displays short wavelength infrared bands 4, 6, and 8 as RGB. In this wavelength region, clay, carbonate, and sulfate minerals have diagnostic absorption features, resulting in distinct colors on the image. For example, limestones are yellow-green, and purple areas are kaolinite-rich. The right image displays thermal infrared bands 13, 12 and 10 as RGB. In this wavelength region, variations in quartz content appear as more or less red; carbonate rocks are green, and mafic volcanic rocks are purple. (Image credit: NASA/Japanese Space Team).

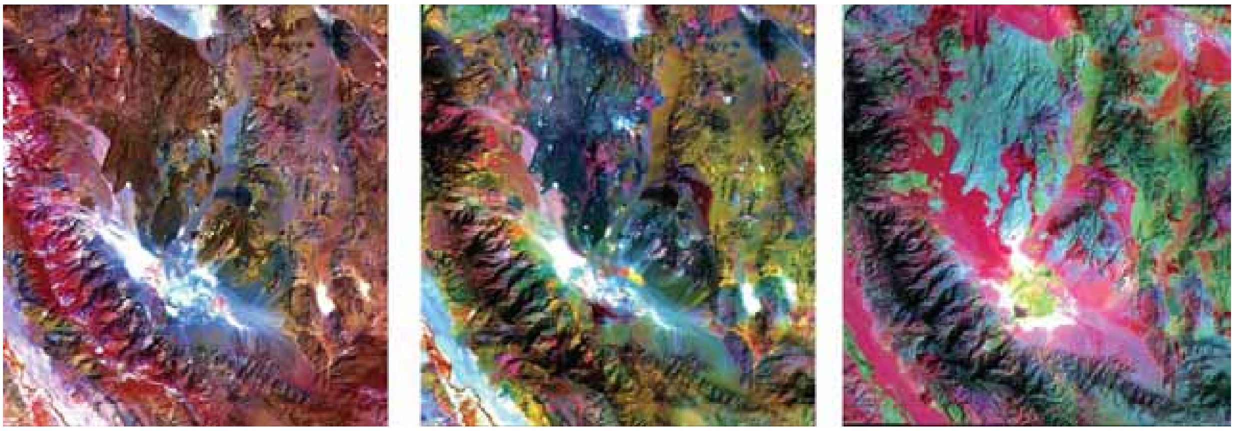

Figure 133 – ASTER images from different spectral regions

Left: VNIR Centre: SWIR Right: TIR

Everett et al. [292] discuss the use of ASTER data for locating major fracture zones and detecting subtle differences in vegetation, soils and rocks related to the presence of hydrocarbons. According to Everett et al. [292], the ASTER instrumentation images the Earth in 14 different spectral bands and these can be used to differentiate between a number of different rock types. The authors use the ASTER data to locate hydrocarbon seepage at the surface and the effects on vegetation. The search for hydrocarbon seepages in vegetated areas is challenging as the response of the vegetation to hydrocarbon in the soil is strongly location specific and depends on a range of factors. However, as seepages occur over a long period of time relative to the vegetation life cycle they do not produce vegetation stress but structural changes in the vegetation community. Everett et al. [292] suggest that the ASTER data were detecting subtle differences in the spectral characteristics of the different vegetation types, which are affected by the water or gas content of the soil.

O'Brien et al. [293] discuss the use of Synthetic Aperture Radar (SAR) data from RadarSat Wide 1 and the ERS satellites. The SAR data have a pixel size of the order of 20 metres and have been used to map oil slicks linked with faults.

Davidson [294] summarises the use of hyperspectral reflectance spectroscopy in the mining industry. This methodology measures the changes in the way the surface reflects light, across a broad spectrum from the visible light through infrared and short-wave infrared to the thermal infrared. These have been used to map different alteration minerals associated with gold deposits in some terrains.

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3.4.4 Applications of SAR Interferometry

Satellite radar interferometry is the use of multiple satellite-acquired SAR data to interpret ground deformation. Data from the ERS-1 and ERS-2 satellites are used. Data sets covering the same area are acquired from the same perspective and are combined to form an interferogram. The phase difference between each pixel of the interferogram is a measure of the local incidence and/or relative change in distance between the ground surface and the SAR antenna. This information is used to compute a digital elevation model (DEM), where height accuracies of better than 10 m and horizontal resolutions of the SAR image resolution (e.g. 20 m) are obtained (Figure 134). Processing and modelling of these data sets can produce deformation maps with centimetre or millimetre accuracy.

BRGM [295] used differential interferometry to measure ground deformation after underground work and water pumping ceased. The results show deformations >3 mm per coloured fringe or ring.

Van der Kooij [296] reports the use of repeat-pass interferometry, and the ability of the technique for measuring ground subsidence and swelling associated with oil and gas fields and mine sites. In particular, the paper looks at the Belridge and Lost Hills Oil Fields (USA) where the subsidence rate is reported to be as high as 30 to 40 cm/y. The subsidence is occurring as a result of compaction driven by pressure reduction associated with the extraction of oil.

Van der Kooij [296] reports that the subsidence areas indicated by the interferograms correspond to the location of the oil wells in the area. The height-change maps can be used to produce deformation maps. An example of a deformation map is shown in Figure 134. Several measurements were performed at 15 locations as shown. This was accomplished by comparing the measurements with the background levels, taken to be the average values west and east of the subsidence. The noise level in the data was estimated to be less than 5 mm.

Van der Kooij [296] considers that satellite-based interferometry provides highly accurate maps of subsidence and is better than conventional ground-based topographic surveys using land-surveying techniques, which are expensive to collect and do not provide such detailed information.

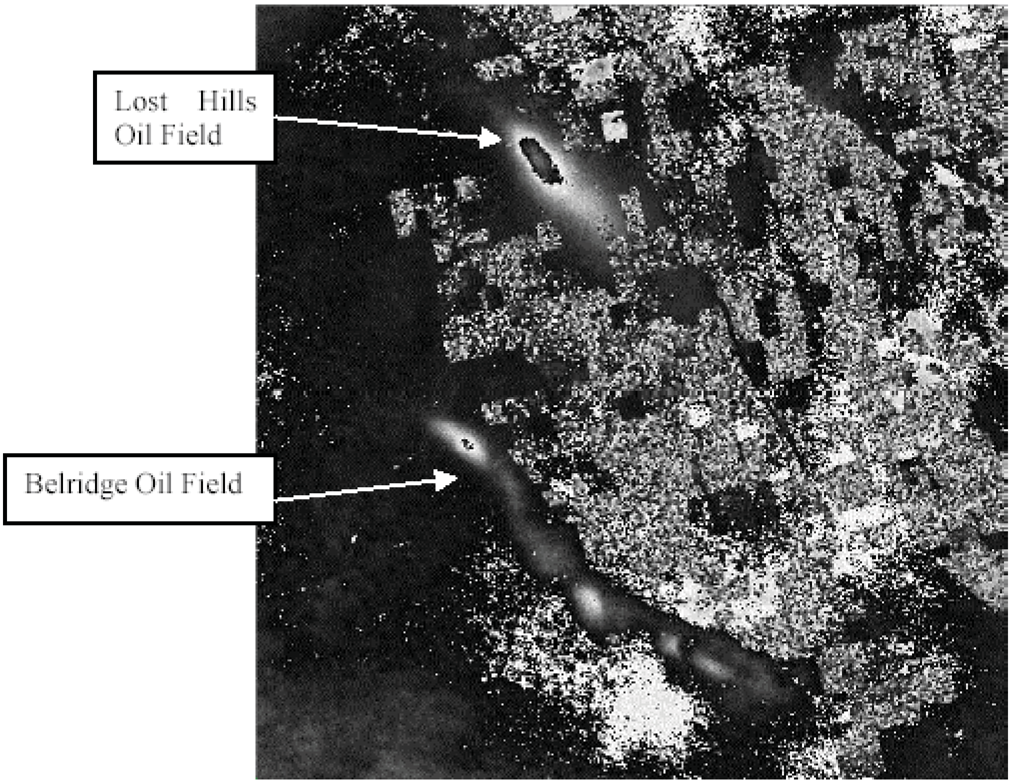

Figure 134: Differential interferogram created from ERS data. The time difference between the two data sets used is 34 days. (After Van der Kooij, 1998).

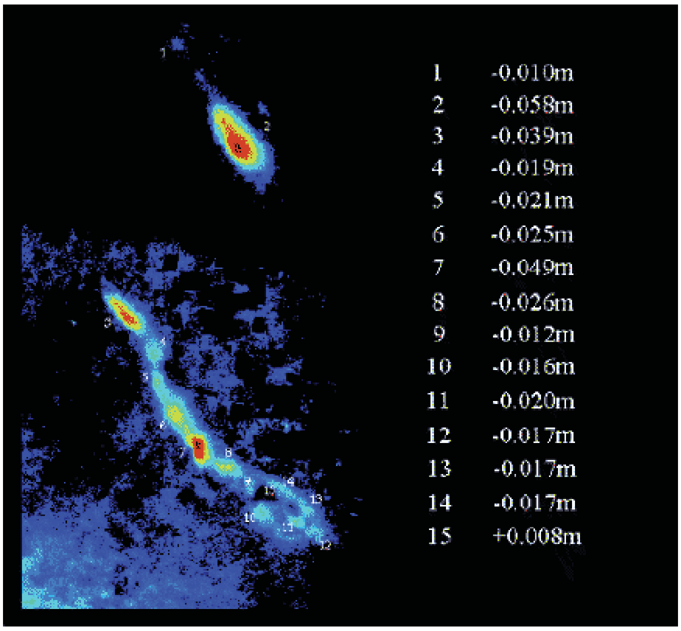

Figure 135: Deformation map generated for 15 sites, with their respective values, derived from one ERS data pair. The figure covers a similar area to that illustrated in previous one.

Ponte [297] notes that satellite-based interferometry and land-based seismic monitoring of an area or an underground facility can be integrated to produce better insight or interpretation of the evolving system.

References

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3.4.5 **Conclusions**

The main conclusions that can be extracted from the review of the non-contact sensing technologies described above are:

- Topographic surveying, although very accurate, is not suitable for the monitoring of terrain deformation over a large region because the measured point cloud it is necessarily sparse.
- Differential InSAR is a very powerful technology to monitor deformations of the terrain surface over the repository, as it can detect vertical motions as small as a few centimetres across a large region. However, the requirement of a minimum coherence between the images used to build the interferogram prevents long-term monitoring based only on this technique, at least in non-arid locations. Either trihedral reflectors could be installed at suitable locations to become permanent scatterers on which to base long-term studies, or a topographic survey of a reduced set of points distributed over the interest region could be routinely made to provide an external reference for DInSAR monitoring.
- Depending on the selected target resolution, terrain images can be acquired either from Earth observation satellites or from airborne sensors. In the latter case, the particular type of platform will have to be decided according to operating costs analysis, but recent developments in UAV technology make the use of this kind of platform very attractive.

4. Techniques evaluation and conclusions

As written at section 2.3 the main interest of MoDeRn project is the monitoring to be carried out during operational and the early post-clossure phases thus the repository and borehole-based techniques. Furthermore, the surface and and aerial based monitoring systems could be applied at every time without interfere with the repository phases, so this chapter will be devoted exclusively to the first two types of monitoring techniques.

4.1 Current limitations and potential improvements

The review of the current status of monitoring technologies has identified a number of limitations for the development of a repository monitoring programme. They are listed by sections.

4.1.1 Repository-based monitoring

Sorted by technology:

4.1.1.1 Classical wired sensors

Common to all parameters:

- Housing materials should be improved to withstand pressure and corrosion, the use of SS316L or Titanium is recommended.
- Same applied to the cables, good jackets of PUR or fluoropolymers (PTFE, FEP, etc) are envisaged and outer metallic protection in SS316L or Titanium could improve the protection degree too in some environments.
- Water and gas insulation should be guaranteed, in especial at the cable entries. Proof testing up to 5 MPa is recommended.
- The behaviour under radiation needs to be asses in almost all cases.

Sorted by parameter:

- Reliable mechanical pressure sensors of reduced dimensions (less than 100mm in diameter) are practically limited to one supplier (KULITE USA) and with delivery times larger than 30 weeks, so additional suppliers are needed.
- Accurate measurement of humidity at the close to saturation stage of buffers and backfills based on bentonite is still not properly solved.
- Related with the previous limitation, reliable sensors to measure pore pressures in unsaturated environments are required.
- Radiation sensors adapted to radwaste monitoring context does not exist.
- Non contact displacement sensors adapted to the harsh repository environment will be welcomed.
- Reliable and stable pH sensors adapted to field conditions and in particular to repository ones need to be developed.
- Colloids sensors do not exist.

4.1.1.2 Fibre Optic sensors

A lot of improvements are expected in this field during the next years but at this stage at least the following improvements are needed:

- Reliability should be extrapolated to other techniques than the interferometric
- Special protection is envisaged to indurate the fibres against water/gas pressure and radiation
- FOS for chemicals, hygrometry and radiation should be developped
- In general these techniques require of further qualification for repository use.

4.1.1.3 Wireless techniques

These systems are only recently under development in relation to deep geological disposal, so a relevant evolution/progress should take place in the next years. According to present results the solutions for repository monitoring could be based on a combination of short/medium range and long range systems, to exploit the advantages of each one and to avoid the drawbacks. The following limitations and potential improvements have been identified for allowing a future practical implementation of wireless monitoring systems:

- Robustness – The presently applied equipment and software are still in the R&D phase. Additional efforts are needed to increase the robustness and to allow for a practical and functional implementation during the disposal process.
- Minimise size (miniaturisation) – One of the main advantages of wireless systems is their non-intrusive nature. Minimising the size of the components embedded in the barriers, without compromising their robustness as pointed out in the previous point, will reduce the perturbation introduced in the repository, specially in constrained areas, and therefore will incerease this advantage.
- Energy limitations – It has been identified that the long-term energy consumption of wireless, stand-alone systems, can be a limiting factor. This applies especially to the power that is required to transmit signals periodically and during many decades from a deep geological repository to the surface. Additional R&D is needed to minimise this energy limitation by 1) increasing the amount of energy available in such stand-alone systems, via the development of new energy sources and the enhancement of the batteries performance, and 2) optimising the energy consumption, via the improvement of energy content per bit of transmitted information and the optimisation of contents and frequency of transmitted signals.
- Susceptibility to radiation – It has to be established whether (γ-) radiation from waste packages adversely affect the long term performance of wireless systems.
- Incorporation of new sensing technologies (compatibility) – Currently, not all kind of sensors can be integrated in a wireless transmitting system. Additional development efforts should be made to widen the range of sensors that can be connected to the nodes, which will open this technology to a larger number of parameters to be measured.
- Demonstration – Several applications of wireless systems have been developed so far. To further evolve the reliability and increase the confidence of such systems additional efforts are needed to demonstrate the applicability of wireless systems under a variety of circumstances.

4.1.2 Borehole-based monitoring

These techniques could be an alternative when no repository based measurements are allowed or when they became inoperative with time. Again a significant improvement should be expected in the future but it seems clear that the resolution will not be comparable to the repository ones: perhaphs they could provide meter scale changes for some parameters instead the cm scale easily provided by the repository-based techniques.

4.2 Results from Monitoring Technologies being developed

The state-of-the-art in monitoring is rapidly evolving thanks to different RTD activities that are constantly extending the capabilities of monitoring technologies. For instance, specific research and technical development of monitoring technologies were carried out as part of WP2 (task 2.3). Complete description and results are provided in Deliverable 2.3.1 [200] but main results achieved are summarised hereafter.

4.2.1 Development of magneto-inductive wireless data transmission techniques with through-the-earth transmission of monitoring data.

The ability to transmit data wirelessly over longer distance (i.e. from the repository to the surface) is an important prerequisite for monitoring during the post-closure phase, in order to support retrievability after closure. A theoretical and experimental (HADES URL) framework for the wireless transmission of data, from a deep geological facility for the disposal of radioactive waste, through subsurface layers of Boom Clay and sandy aquifers, to the earth's surface has been elaborated. The specific objective was to characterize and optimize the energy use of this technique within the specific context of post closure monitoring.

From the potential technical options available, the use of low-frequency magnetic fields was judged as most feasible for the projected application. The performed analyses show that, although some uncertainties exist and some parameters need to be provided experimentally, a framework can be developed that allows the estimation of general features and parameters necessary to set-up a system for data transmission from a subsurface disposal facility to the surface. This research was successful in demonstrating wireless transmission of data through 225 m of an electrically highly conductive geological medium at the HADES URL, Mol, Belgium, using frequencies up to 1.8 kHz. Transmission rates up to 100 sym/s were demonstrated and Bit Error Rates (BER) below 0.1% were achieved.

This illustrates that the technology developed within the MoDeRn Project is suitable for transmitting data over longer distances through the subsurface. In terms of energy use, the lowest energy use realized was about 1 Ws/bit. However, under more favourable conditions, the energy efficiency of the used technology is expected to be much higher, and for application cases where larger transmission antenna can be applied (e.g. generic Dutch disposal concept in Boom Clay at 500 m depth), an energy use below 1 mWs/bit should be achievable.

Although it should be noted that the performed analyses are based on a number of generalisations and assumptions, the obtained result can be used to estimate the energy use for other disposal situations. An important factor with respect to analyses of any disposal systems is the electrical conductivity of the host rock: the conductivity of rock salt, granite or Opalinus Clay is much lower than in case of the experiments performed at the HADES URL, allowing the use of higher transmission frequencies and data rates that favours higher energy efficiencies in these host rocks.

4.2.2 Improvements to the interpretation algorithms used for interpretation of cross-hole seismic tomography data.

Controlled source seismic tomography (Marelli, 2012) offers the potential for high-resolution imaging of the EBS. Seismic imaging is based on the fact that any heterogeneity in the elastic properties of the medium (e.g., seismic wave speed, density and attenuation) affects the wave propagation characteristics, and so diagnostic changes in the waveforms (travel times, amplitudes, pulse shape) could be observed. Tomographic imaging allows a detailed image of the subsurface elastic properties.

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

The work undertaken focused on full waveform inversion of seismic tomograms, as the low density of the EBS compared to the host rock means that travel time-based approaches are unsuitable (they concentrate on the first arrivals, which follow paths that do not intersect the EBS). It included the development of techniques for improving the repeatability of the seismic measurements, developing a better understanding of the elastic properties of bentonite and the development of suitable tomographic inversion algorithms. These developments were applied to, and tested against, the experimental set-ups in Grimsel and Mont Terri.

The research undertaken significantly advanced the potential for using seismic tomography to monitor the EBS, by:

- Providing criteria for establishing optimal spatial and temporal sampling strategies
- Revealing that the acoustic approximation is not adequate for monitoring radioactive waste repositories and that elastic inversion schemes should be used instead.
- Showing in which situations the inversions are expected to be successful and when they are likely to fail due to the non-linearity of the seismic waveform problem
- Implementing an anisotropic and elastic waveform algorithm
- Developping and testing an algorithm that can be used to reliably determine the coupling factors.

4.2.3 Development of fibre optic sensors for distributed temperature sensing and for monitoring of cement-based materials.

Research into optical fibres has been undertaken within the research, development and demonstration programme associated with the PRACLAY Heater Test in the HADES URL in Belgium. The thermal-mechanical response of the PRACLAY gallery will be monitored using a distributed fibre optic monitoring system emplaced on the inside of the PRACLAY gallery. The main phase of the Heater Test – the heating itself – has not yet started as the gallery seal has not yet obtained the required hydraulic conductivity and swelling pressure owing to an unexpected slow rate of hydration and swelling of the bentonite.

Three sensors have been installed in series in each of three 20m long boreholes to monitor the (thermal) expansion of the host rock following the heating in the PRACLAY Gallery. Each borehole contains three sensors to obtain multiple strain measurements. The sensors consist of two fibres inside protective tubing, with one fibre being attached to two anchor points at both ends of the tubing, and another fibre of similar length which is loose inside the tubing – it is expected that the length of the latter fibre is not influenced by the change of length between the anchor points. The difference between the two fibres can then be monitored by interferometery. The aim of this work is to improve our understanding of the use of optical fibres for this technique and what adaptations might be required for this type of sensor.

The measurements that have been obtained so far show that these sensors are able to quantify displacements with a resolution of 1 µm. Based on other quality factors, such as repeatability, the accuracy can be estimated to be less than 10 µm for a measurement base of 10 m. This permits monitoring of very slow movements – typical for long-term repository processes.

4.2.4 **Development of high-frequency wireless monitoring sensor networks and wireless data transmission using high-frequency signals**.

Development of wireless data transmission methods would allow for data measured by sensors emplaced within the EBS to be relayed to receiving stations, and would, therefore, represent a method for monitoring of the EBS without affecting the passive safety of key design components (e.g. plugs and seals) by short-circuiting their containment function through the introduction of wires. The sensors that could be emplaced within the EBS would be based on traditional technologies with adaptations to reflect the anticipated environmental conditions.

High-frequency wireless data transmission considers transmission of data in the very-high frequency (VHF) and ultra-high frequency (UHF) bands. These wave bands have a higher data rate capability than lower frequency wave bands, which results in shorter transmission times and lower power consumption. However, the penetration of data through rock at high-frequencies is much lower than for data transmitted at low-frequencies (see 4.2.1)

Initial work focused on designing appropriate wireless nodes by evaluating, at different frequencies, the limiting distances for remote transmission through solid media and the capacity and rate for transmitting data at those frequencies relative to energy requirements. The research and demonstration activities (tested on the same shotcrete plug at the Grimsel Test Site that was used for the demonstration of seismic tomography) aimed at demonstrating, under realistic conditions, the potential for underground use of high-frequency wireless nodes to build data transmission networks of conventional sensors, which could be placed within the EBS (buffer, concrete, rock, etc). The research and demonstration also considered the management of the corresponding energy needs for operating in an inaccessible location over decades.

The result is a communication system comprising a master controller unit, to be installed in a service area, controlling a number of wireless nodes to be placed within the sealed areas. The development of the different parts of the system was performed using radio transceivers (two way radio systems) tuned at 169 MHz. The use of bi-directional and also multi-channel radio interfaces allows the system to change the monitoring strategy in real time, by sending remote commands to the wireless nodes, and makes possible the co-existence of more than one independent monitoring systems in the same scenario without interfering one another.

The wireless nodes are based on radio units certified according to ETSI EN 300 220-3 & EN 301 489-3 standards, having a maximum transmission power of 500 mW (+27 dBm). Each one can negotiate up to 4 typical analog sensors with voltage or current output and 3 digital sensors, supplying power to the sensors, collecting their readings through short cables and performing a previous analysis of the signal to detect possible reading failures, and repeating the process when necessary. The nodes have been designed to withstand the harsh environmental conditions inside the monitored area including high pressure, high humidity and temperature levels, etc

Additionally, the feasibility of power harvesting to conserve the power source (battery) and to extend the period of monitoring was also evaluated. Research into power supply considered energy harvesting using thermal gradients and high-performance batteries. Thermal gradients can be used as a power source, based on the Seebeck effect. A temperature difference of 15°C would be sufficient to provide a power of 1,100 μW, which, in turn is sufficient to power a high-frequency wireless node. However, the energy required to transmit the data must be stored, and existing super capacitors have leakage rates of the same order as the power that could be generated. Therefore, the wireless nodes developed for the MoDeRn Project used a Li-$SOCl_2$ battery combined with some high performance capacitors that support high current demands and have a low leakage current (of the order of a few nA). The final design for the nodes used is for a small self-contained device with an expected lifetime up to 20 or 25 years.

4.3 Current status of the Monitoring Technologies

According to the current state-of-the-art, the results obtained from the carried out R&D activities and the results obtained from more recent projects having monitoring systems for determining the THM evolution of the repository components, it can be stated that there are already techniques available to develop the future repository monitoring programmes. Nevertheless, it is also clear that a potential margin of improvement exists (see paragraphs 4.1 and 4.2) and that the means to promote such developments should be provided. In this sense, Technology Readiness Level methodology (TRL, see [298], [299]) provides an objective method to evaluate the degree of development of different technologies. In the future, a review of the state of the art of the different techniques involved in a repository monitoring programme using this methodology could be of interest.

This is especially true for techniques to be applied in the vicinity of the waste (if any), those classified as repository or borehole based, because remaining ones could be applied at every time (not constrained by the physical limits of the repository).

In this sense a reliable solution for avoiding the cables is necessary and further efforts should be made to obtain a reliable and qualified solution for the data transmission using wireless techniques. Same applies to FOS that will reduce the number of cables due to the multiplexing capability.

Finally the borehole based techniques requires of further development too to provide an alternative when the repository-based techniques conclude their operative life.

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4.4 Long term data management and signal analysis

In order to support decision making during the stepwise implementation of geological disposal, there needs to be confidence in the data on which decision making is based. Accurate data acquisition requires a chain of sensors, cables, connectors, analogue-digital-converters, data-acquisition units, data-processing units, correction and calibration methods, and data transmission units all working to specification. Therefore, the quality of monitoring data does not only rely on the monitoring devices itself, but also on the proper operation of each of the given components, and as it is the monitoring results and not the sensor readings that will be used for decision making, statements on quality beyond the sensor level are required. This is referred to as the *method* level of monitoring system failure detection. Furthermore, aspects like redundancy or the correction for cross-sensitivities are part of a higher-level approach that can address data quality. This is referred to as the *procedure* level of monitoring system failure detection. Failure of a monitoring system is defined as an instance when the outcome of implementing the monitoring system does not comply with the specified response to chemical and/or physical phenomena. Error detection is regarded as a sub-set of monitoring system failure.

Potential failure modes have been studied as part of WP4 of MoDeRn project [300] and it was concluded that in numerous and widely varying safety-relevant areas different methods to detect errors and failures have been developed, many of which are applicable to repository monitoring. These vary with respect to the degree of reliability that can be achieved, the technical efforts necessary and the special requirements of the particular application.

The relation between detection methods and failure modes gives a first idea of which failures modes may stay potentially undetected and which modes are less challenging (e.g. a simple sensor breakdown is easily identified by redundancy). It also shows what (combination of) measures/techniques are effective in addressing failure modes. By selection of principal techniques that are favourable with respect to failure detection, the ability to identify potential failures of the monitoring system can be improved. Understanding of the relation between failure detection and different techniques may also help to identify additional monitoring techniques or measures that can be applied in order to address as much failure modes as possible. One possibility to increase the reliability of sensor readouts is the use of safe sensors. Since sensors will be implemented for repository monitoring purposes, especially for long-term monitoring of disposal cells after their closure, the focus could be put on the use of fail-safe sensors. These systems make use of error detection methods and apply these methods in a predefined, automated manner.

Robust methods and procedures that qualify all aspects of the performance of the applied monitoring systems are essential to allow the data to be used in decision making. Owing to the long timescales and the fact that sensors or other components of the monitoring equipment may be inaccessible, repository monitoring is challenging, and the possibility of failure detection will be an important aspect of the robust methods that need to be developed. Looking at the examples of applied failure detection methods and detection procedures at the different URLs in Europe it is clear that the opportunity for focussed development and application of such methods and procedures is currently limited. This is due to the fact that monitoring techniques are generally applied as part of research projects. The experiments performed are often limited in time and thus no real long-term monitoring over several decades is possible. Under these circumstances, there will always be the possibility to recover the implemented sensors and check for any performance changes or failures, so there is not an absolute need for a fail-safe sensor to be used in the short-term experiments. However, when it comes to the detection of failures, several specific features of monitoring in waste disposal can be used:

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

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[300] MoDeRn Project (2012). Failure Detection Methods for Repository Monitoring.

4.5 Conclusions

This report provides a comprehensive overview of state of art on technologies relevant for use in a repository context. All information was justified with available references, feedback and experience, highlighting the advantages and disadvantages.

Furthermore, the maturity and applicability of the reviewed techniques are evaluated for the repository monitoring program development, and further improvement and R&D lines are proposed too.

A big effort has been made to collect all this information and to put it together in a comprehensive way, ensuring that this will help to take future decisions on the design of the repository monitoring programs. Nevertheless, some of the techniques considered here are rapidly evolving and therefore the content of the report will require of periodical update.